Electromagnetic Probes
PHENIX results

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Stony Brook University
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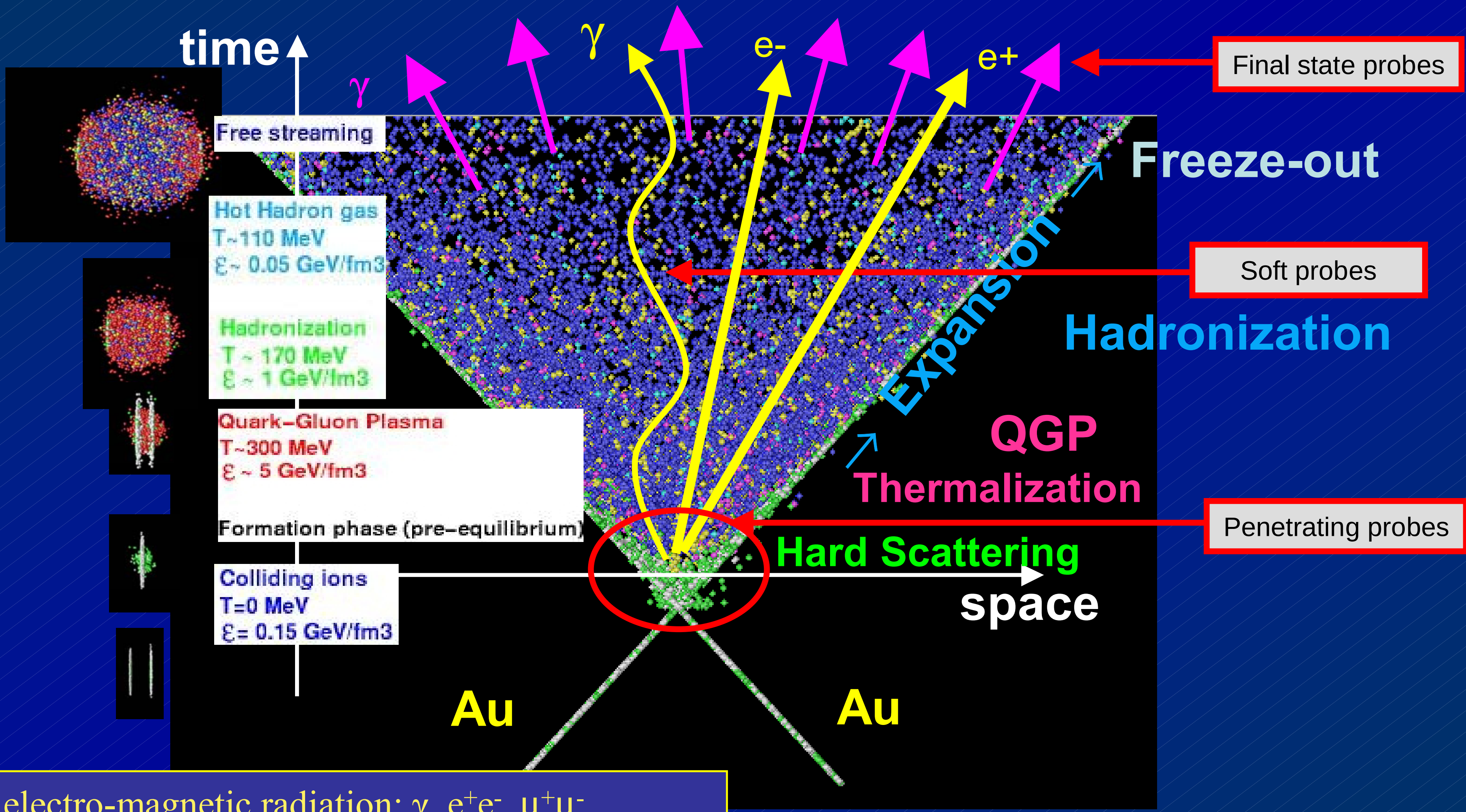
Outline

- Motivation
- Photon Measurements
  - Direct photons in p+p, d+Au and Au+Au
  - External Conversions
  - Low mass internal conversions
- Dielectron continuum
- Summary

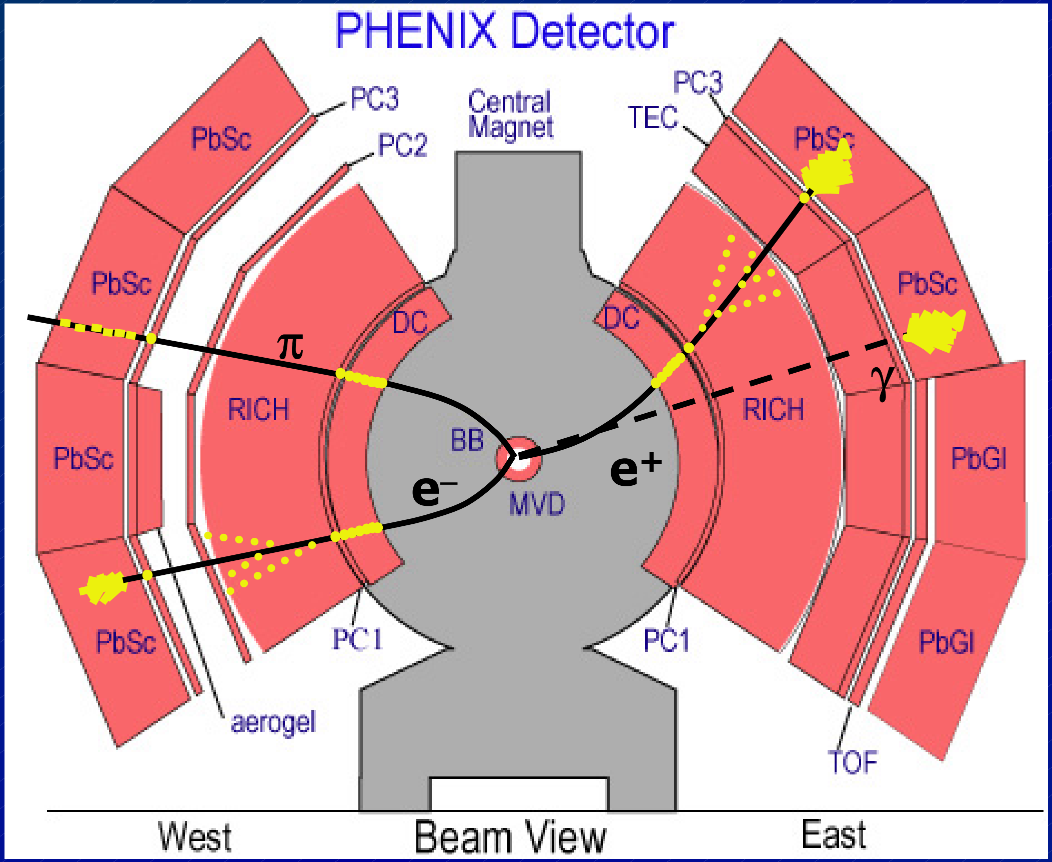
The "Little Bang" in the lab



electro-magnetic radiation: γ, e^+e^-, $\mu^+\mu^-$

rare, emitted "any time"; reach detector unperturbed by strong final state interaction

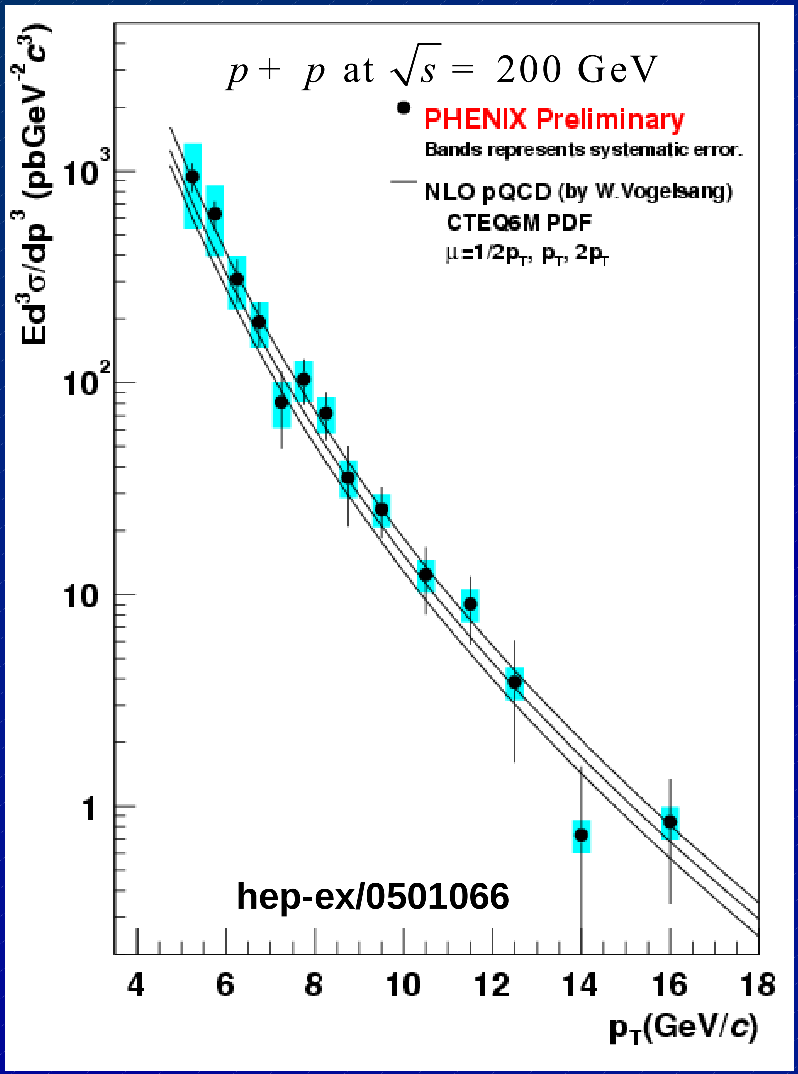
The PHENIX experiment



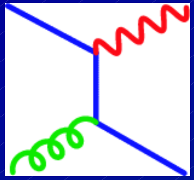
- Charged particle tracking:
  - DC, PC1, PC2, PC3
- Electron ID:
  - Cherenkov light RICH
  - shower EMCal
- Photon ID:
  - shower EMCal
    - Lead scintillator calorimeter (PbSc)
    - Lead glass calorimeter (PbGl)
  - charged particle veto

- **Photon measurements**
  - **Calorimeter measurement**
  - Beam pipe conversions
  - Internal conversions
- Dielectron continuum

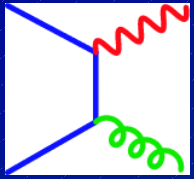
Direct photons in p+p



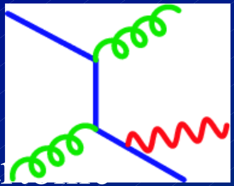
- Direct photon sources:
  - Compton



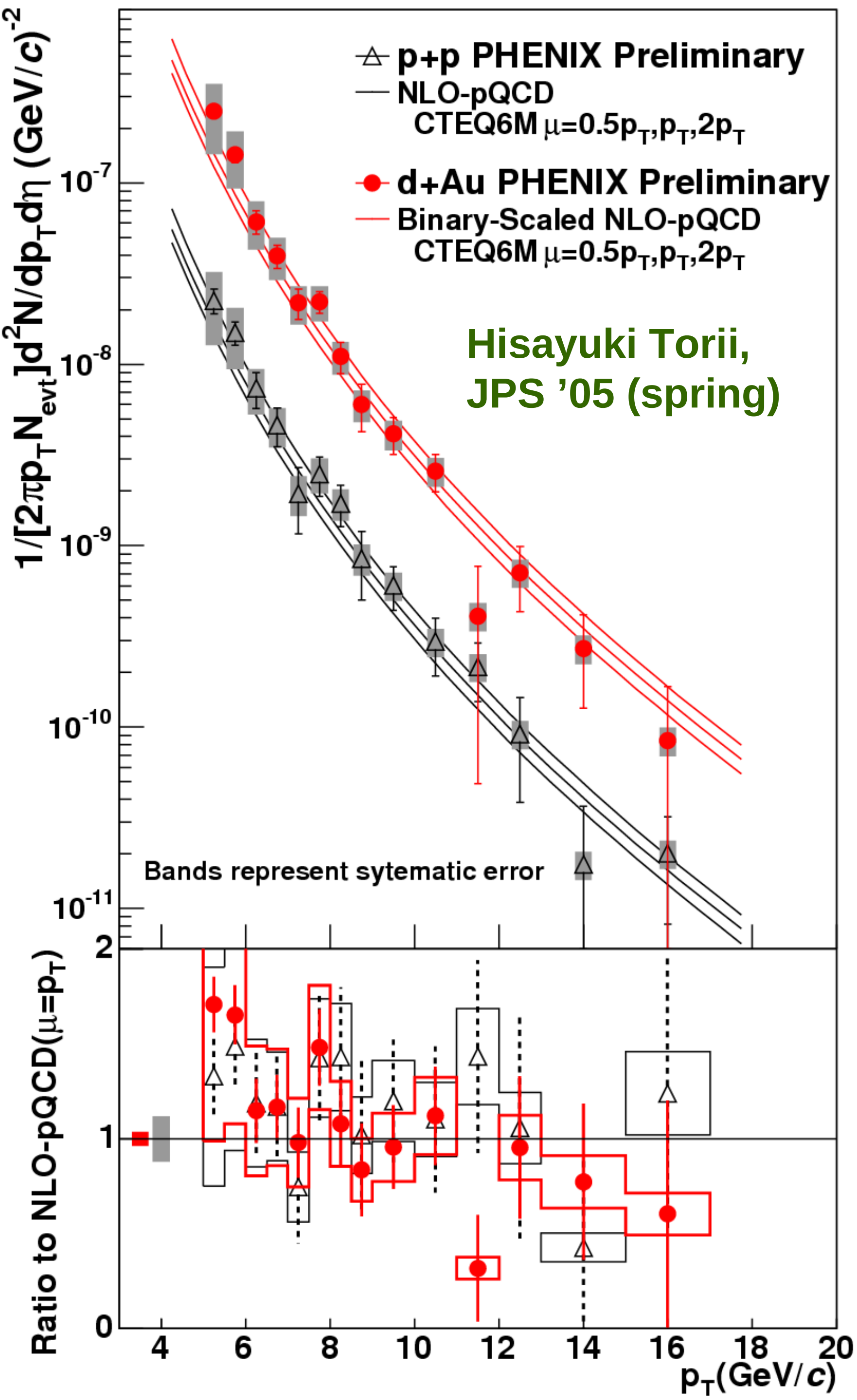
    $qg \rightarrow \gamma q$
  - Annihilation



    $q\bar{q} \rightarrow \gamma g$
  - Bremsstrahlung



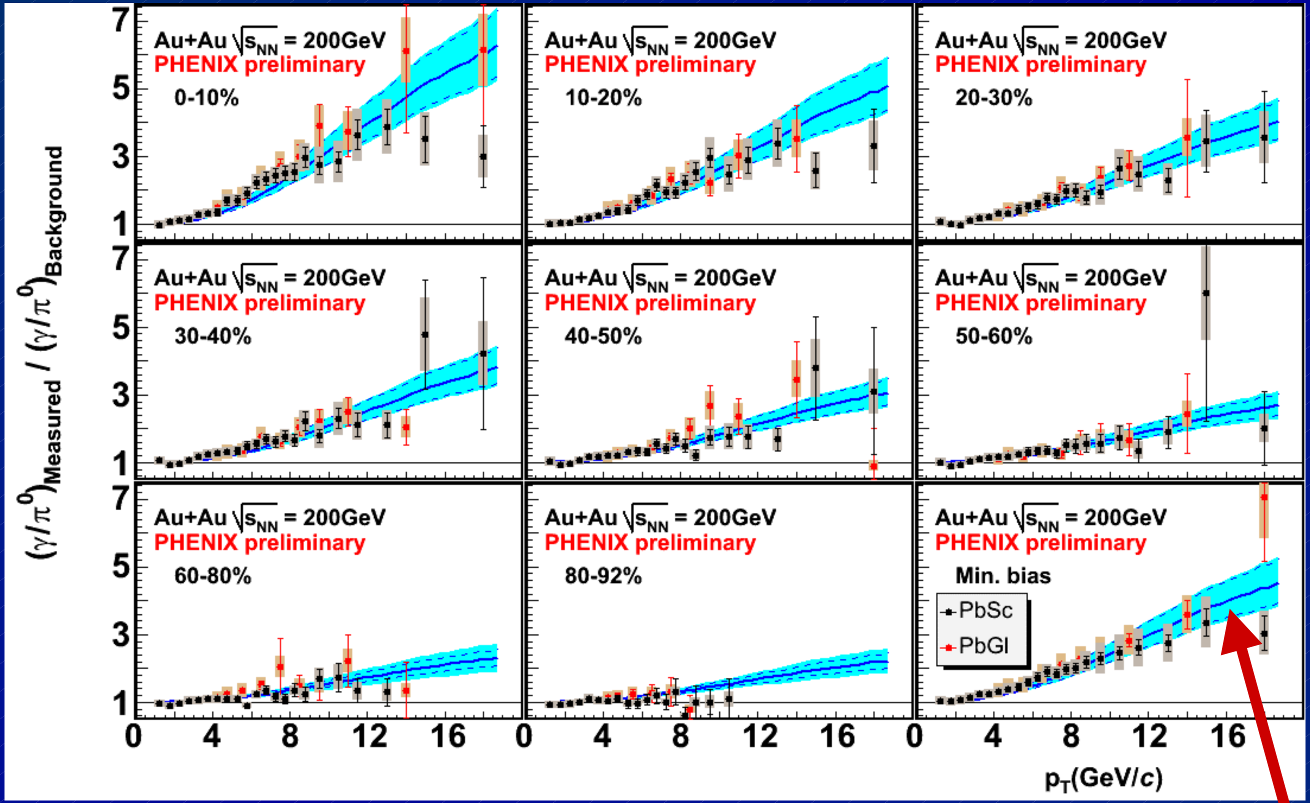
- Test QCD
  - direct participant in partonic interaction
  - Less dependent on FF than hadron production
- good agreement with NLO pQCD
- Baseline for Au+Au



Direct photons in d+Au

- Probe cold nuclear matter
- Study initial state effects
- NLO pQCD comparison agrees with 1:
  → no indication for initial state effect on photon production
  (but large uncertainties)

Direct photons in Au+Au



- Probe the medium
- Photons from all stages of the collision
- Unaffected by the QGP
- Large direct photon excess

N_{coll} scaling of hard processes holds for all centrality classes

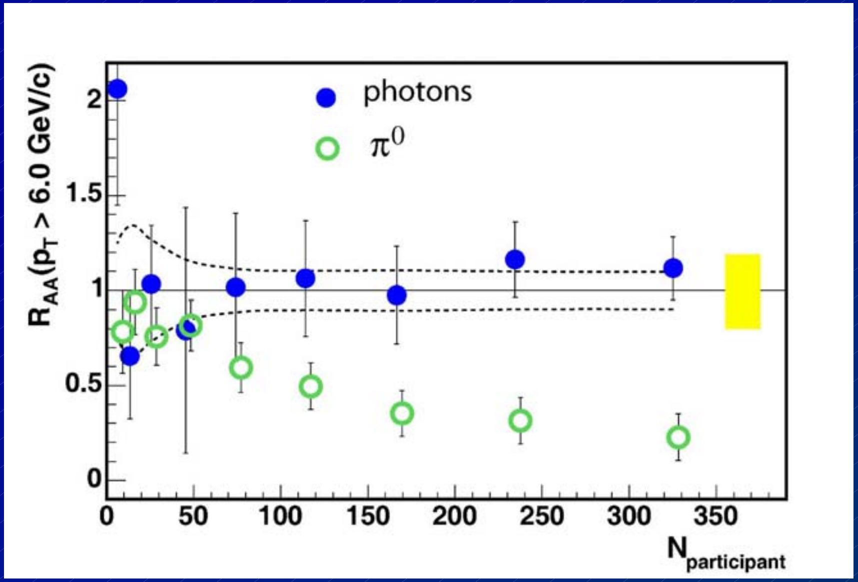
Hadron suppression

- π^0 suppressed
- Photons remain unsuppressed

→Suppression is not an initial state effect

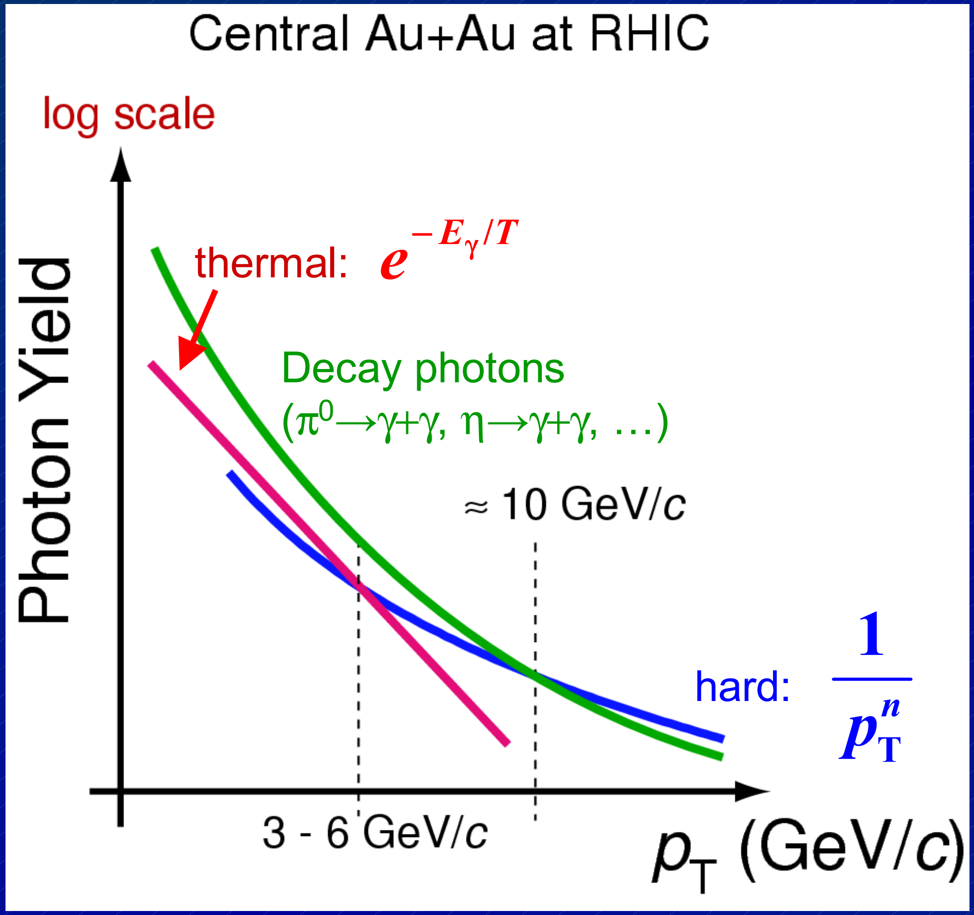
→Evidence for medium effect

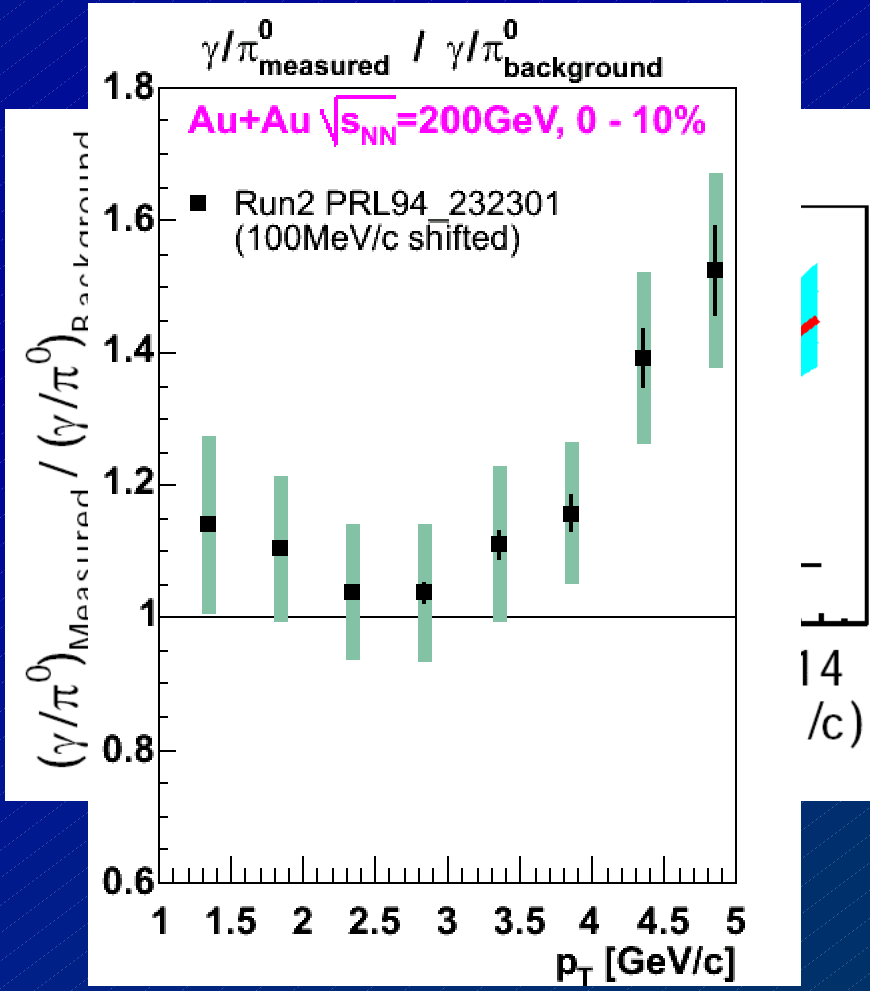
$$R_{AA} = \frac{dN_{AA}^{\pi^0} / dp_T}{\langle T_{AA} \rangle_f \, d\sigma_{NN}^{\pi^0} / dp_T}$$



PRL 94, 232301 (2005)

Thermal photons?





No significant excess at low p_T

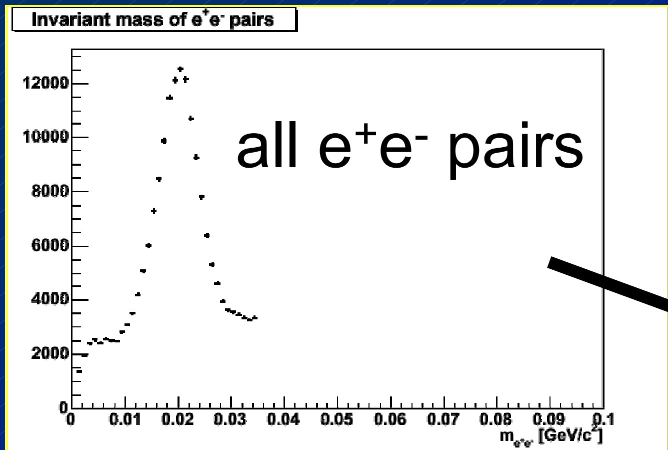
- **Photon measurements**
  - Calorimeter measurement
  - **Beam pipe conversions**
  - Internal conversions
- Dielectron continuum

The idea: photon conversions

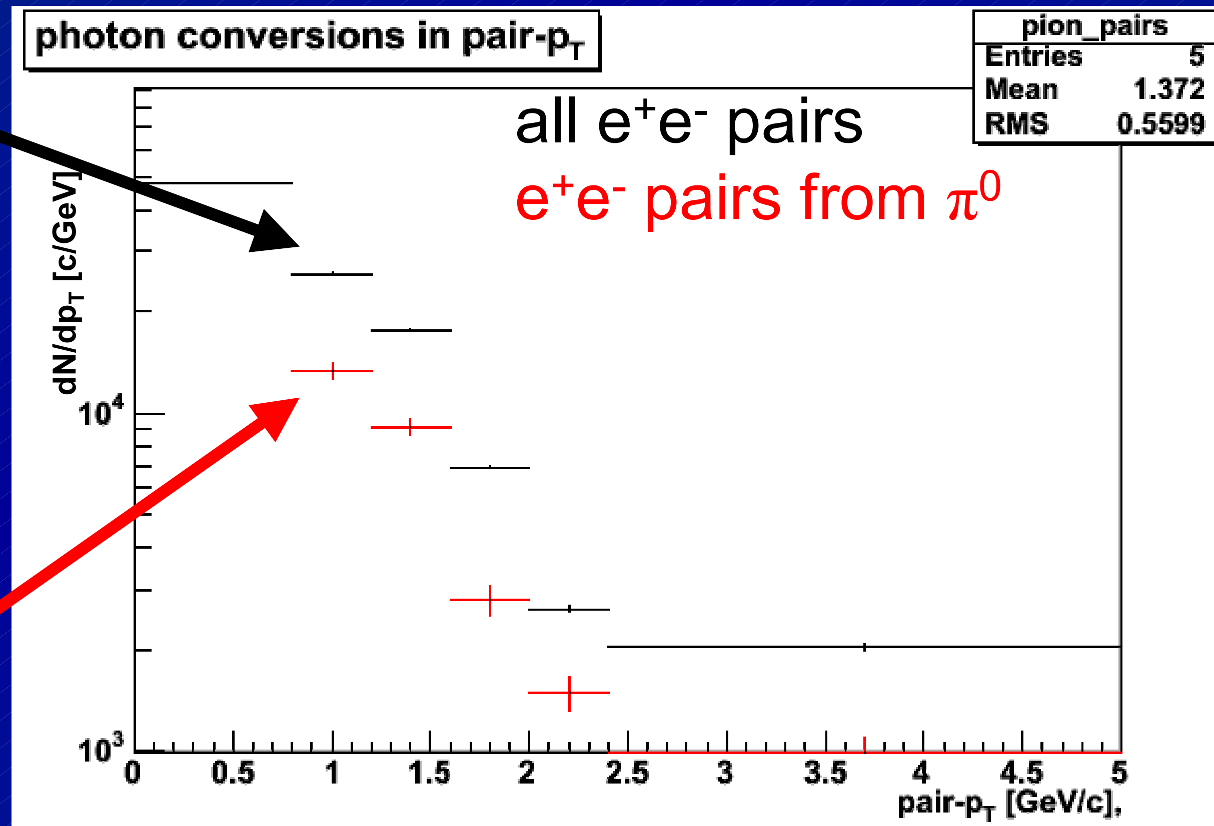
- Clean photon sample: e^+e^- pairs from beam pipe conversions
- Why?
  clear photon identification
  Very good momentum resolution of charged tracks at low p_T
- Procedure
  - Identify conversion photons in the beam pipe
  - Tag π^0 by pairing electron pairs from conversions with photons in EMCal
  - Do the same in simulations
- Double Ratio + π^0 Tagging: efficiencies and acceptance corrections cancel out

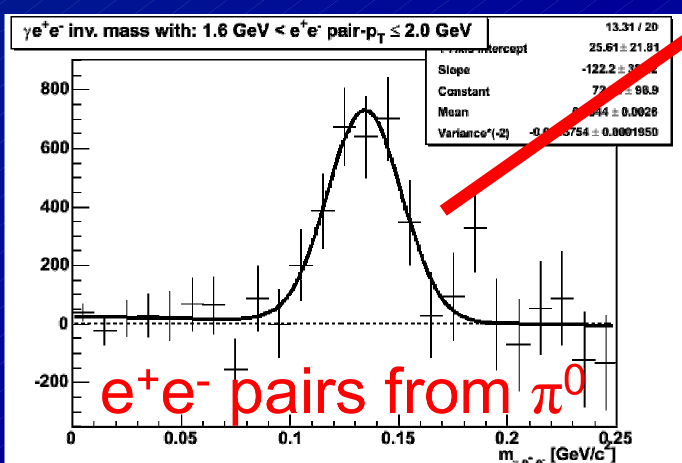
For details, see poster presentation

Inclusive photons/tagged photons from π^0



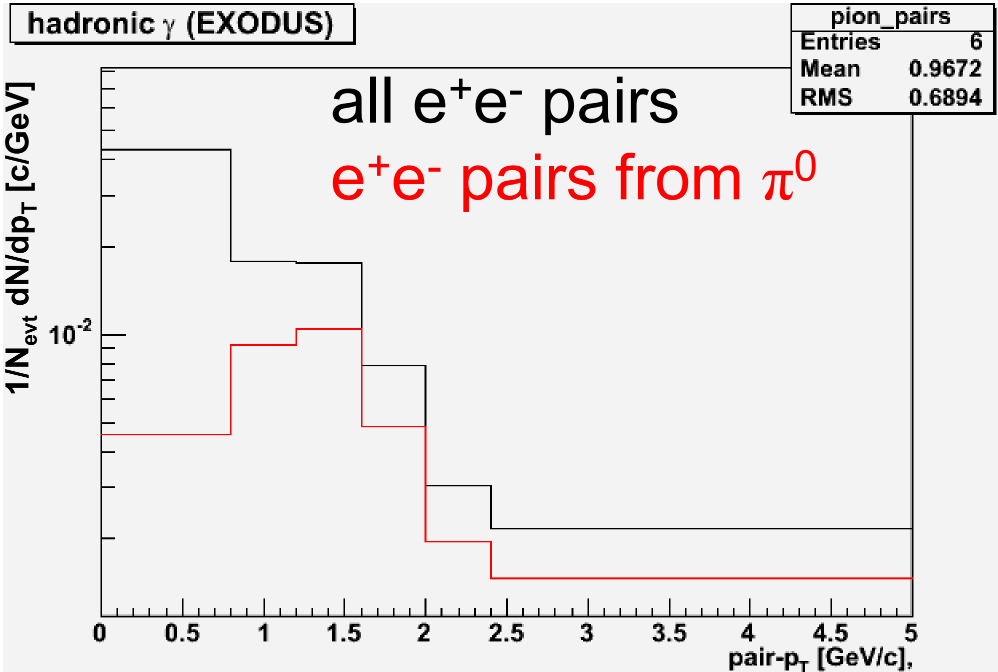
- Conversion pairs are created off-vertex
- Track reconstruction produces apparent opening angle
- Leads to apparent mass ~20MeV/c²
(m ~ conversion radius)
- Cut on pair orientation in magnetic field to isolate conversions



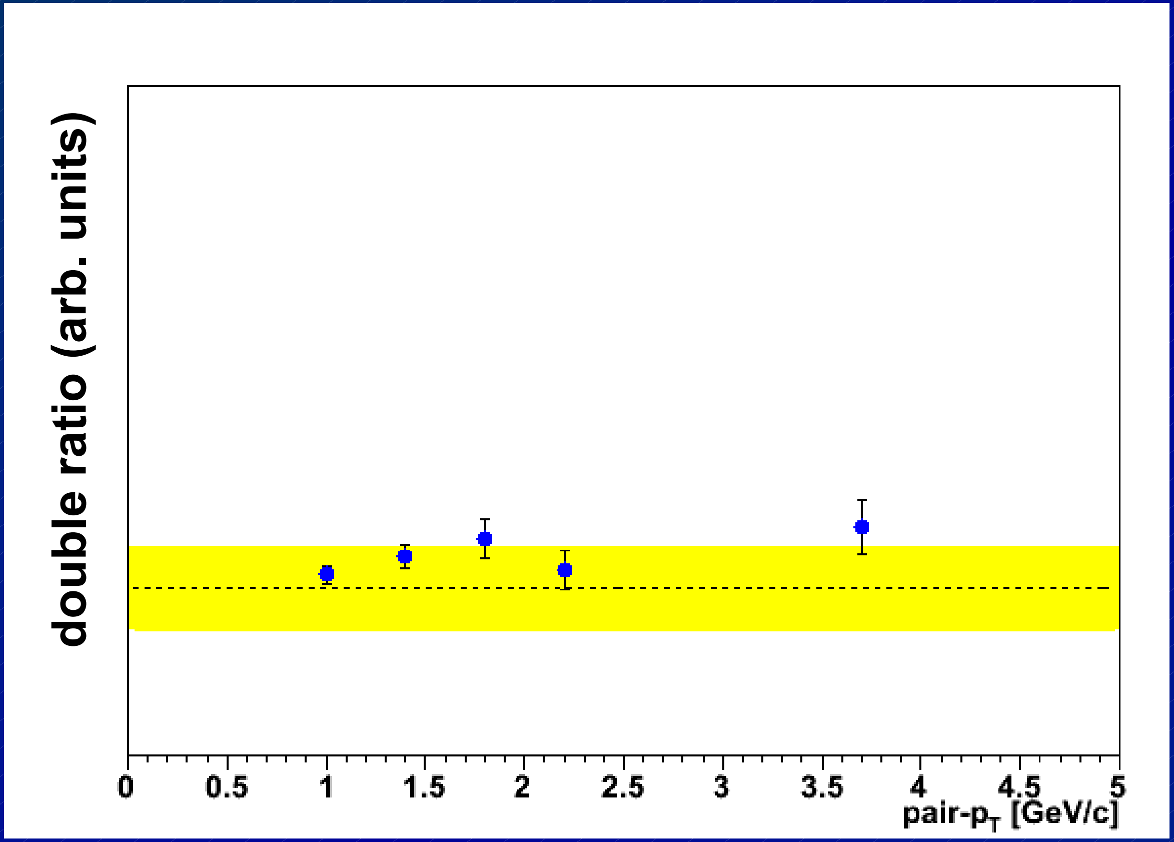


Simulations: hadronic photons/tagged photons from π^0

- Inclusive photon spectrum
  - $\pi^0, \eta \rightarrow \gamma e^+e^-$
    - π^0 parameterization from measured data
    - η from m_T scaling, yield normalized at high p_T (0.45 from measurement)
  - Use Dalitz decay ($\pi^0 \rightarrow \gamma\,\gamma \sim \pi^0 \rightarrow \gamma\,\gamma^* \rightarrow \gamma e^+e^-$ for $p_T > 0.8$ GeV/c)
- All e^+e^- (from π^0, η) in the acceptance → p_T spectrum of e^+e^-
- If γ from π^0 is also in acceptance →p_T spectrum of e^+e^- from π^0



Double ratio of data and simulations



Systematic uncertainties:

- conversion background 6%
- π^0 background 20%
- reconstruction efficiency 3%
- agreement of conditional acceptance 10%

→ total: ~25%

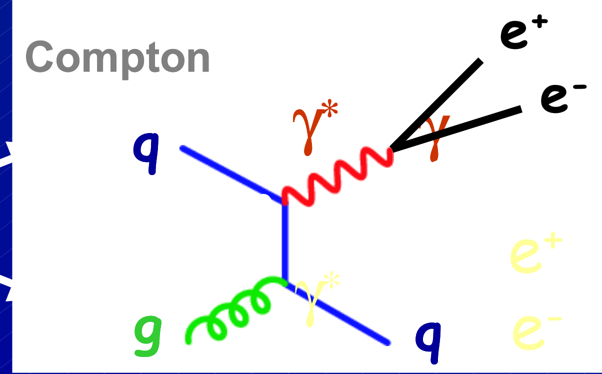
Systematic errors will improve

- Photon measurements
  - Calorimeter measurement
  - Beam pipe conversions
  - **Internal conversions**
- Dielectron continuum

The idea

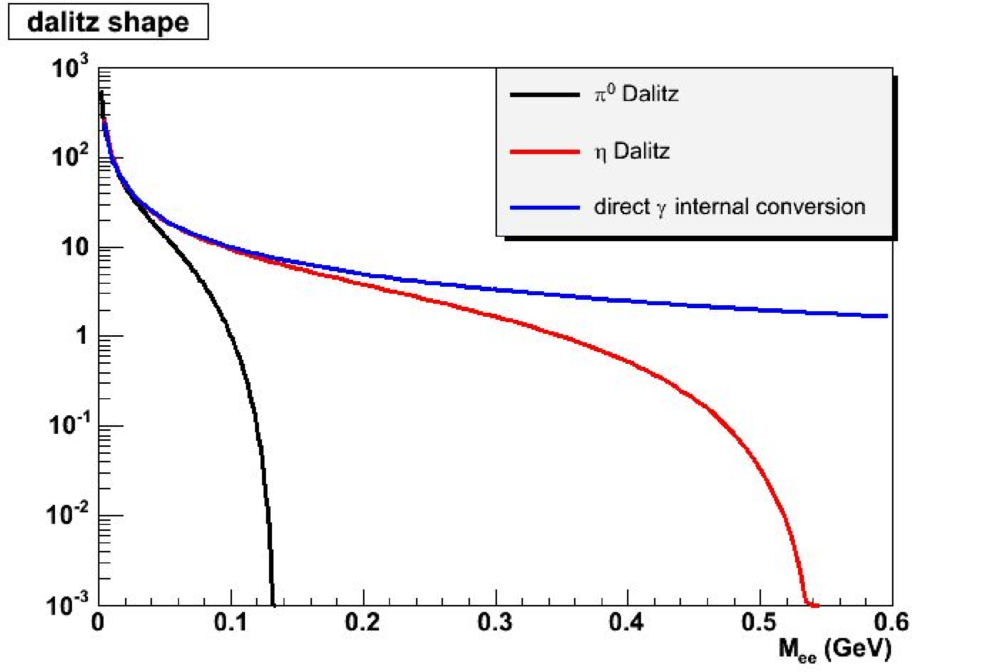
- Start from Dalitz decay
- Calculate inv. mass distribution of Dalitz pairs'

π^0



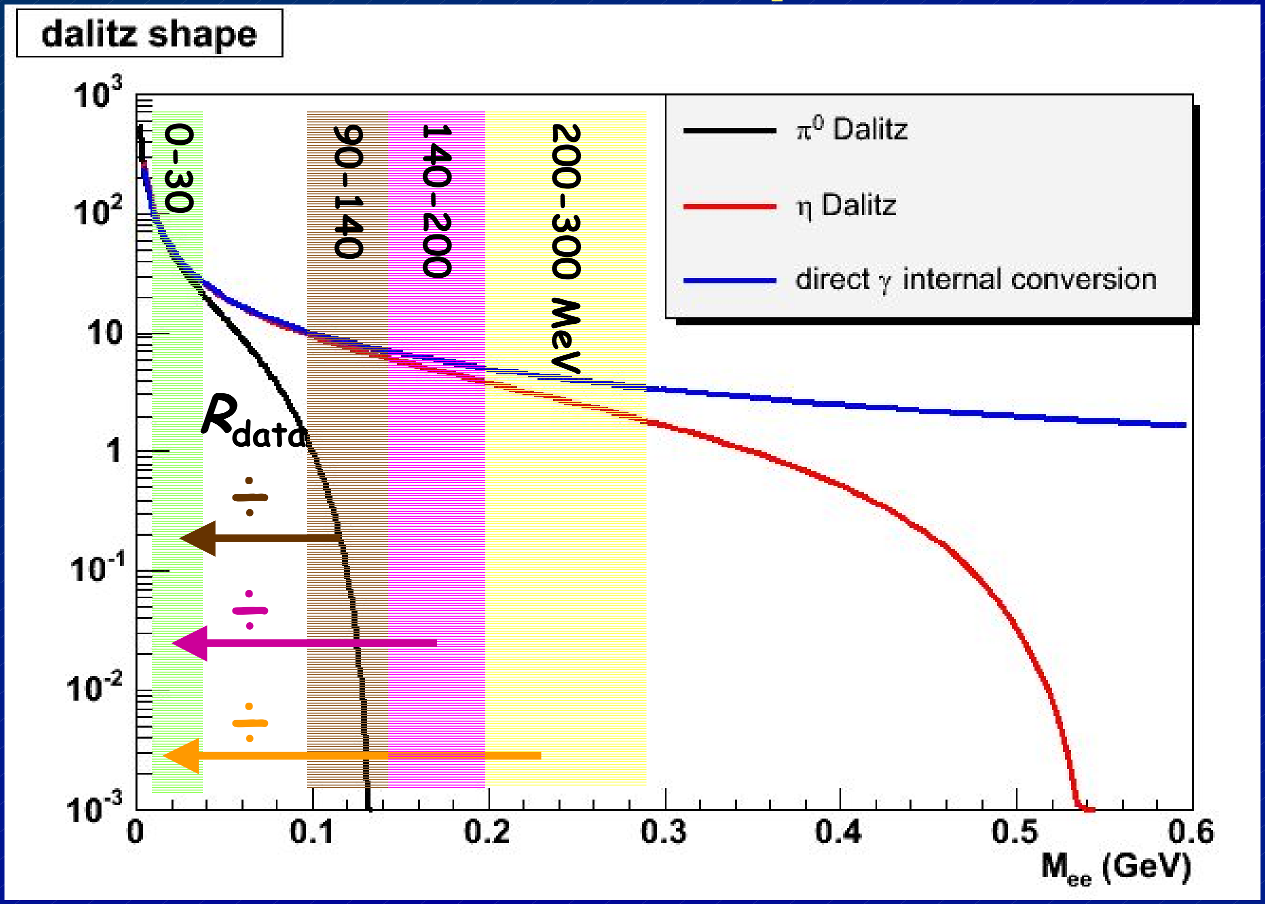
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}\left|F(m_{ee}^2)\right|^2\left(1-\frac{m_{ee}^2}{M^2}\right)^3$$

invariant mass of Dalitz pair	invariant mass of virtual photon	form factor	phase space factor



- Now direct photons
- Any source of real γ produces virtual γ with very low mass
- Rate and mass distribution given by same formula
  - No phase space factor for $m_{ee} \ll p_T^{\text{photon}}$

In practice

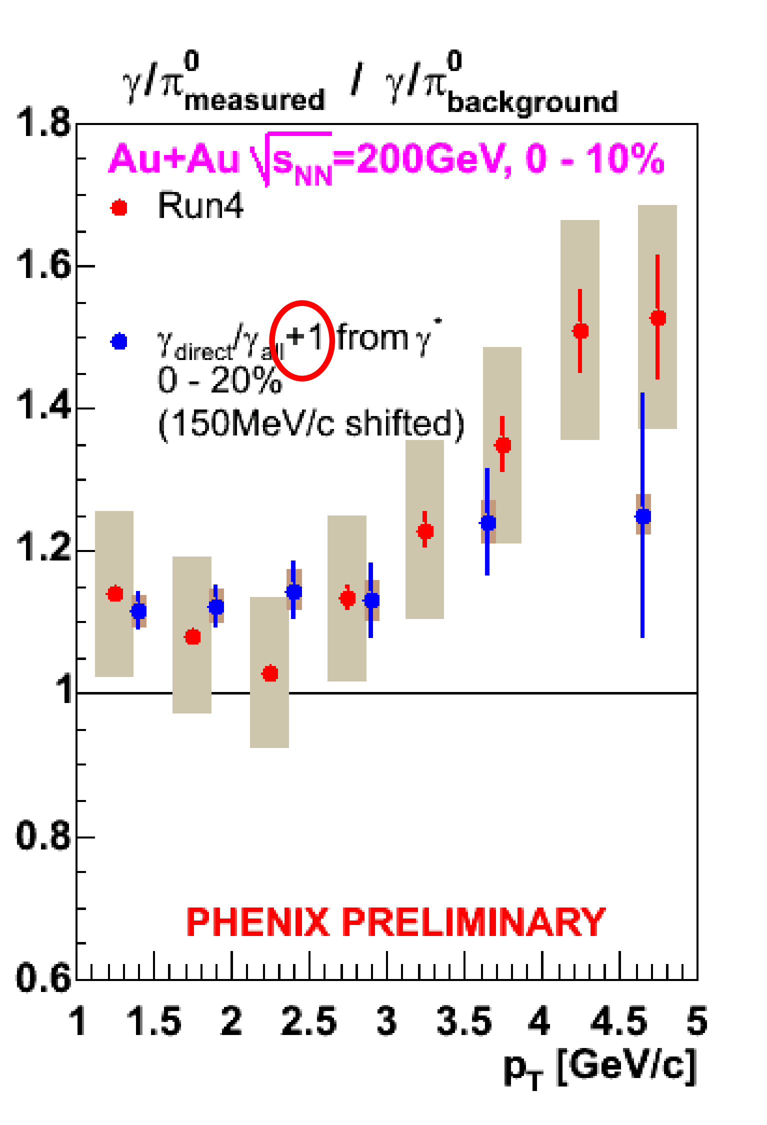


Material conversion pairs removed by analysis cut

Combinatorial background removed by mixed events

- Calculate ratios of various M_{inv} bins to lowest one: R_{data}
- If no direct photons: ratios correspond to Dalitz decays
- If excess: direct photons

Comparison to conventional result

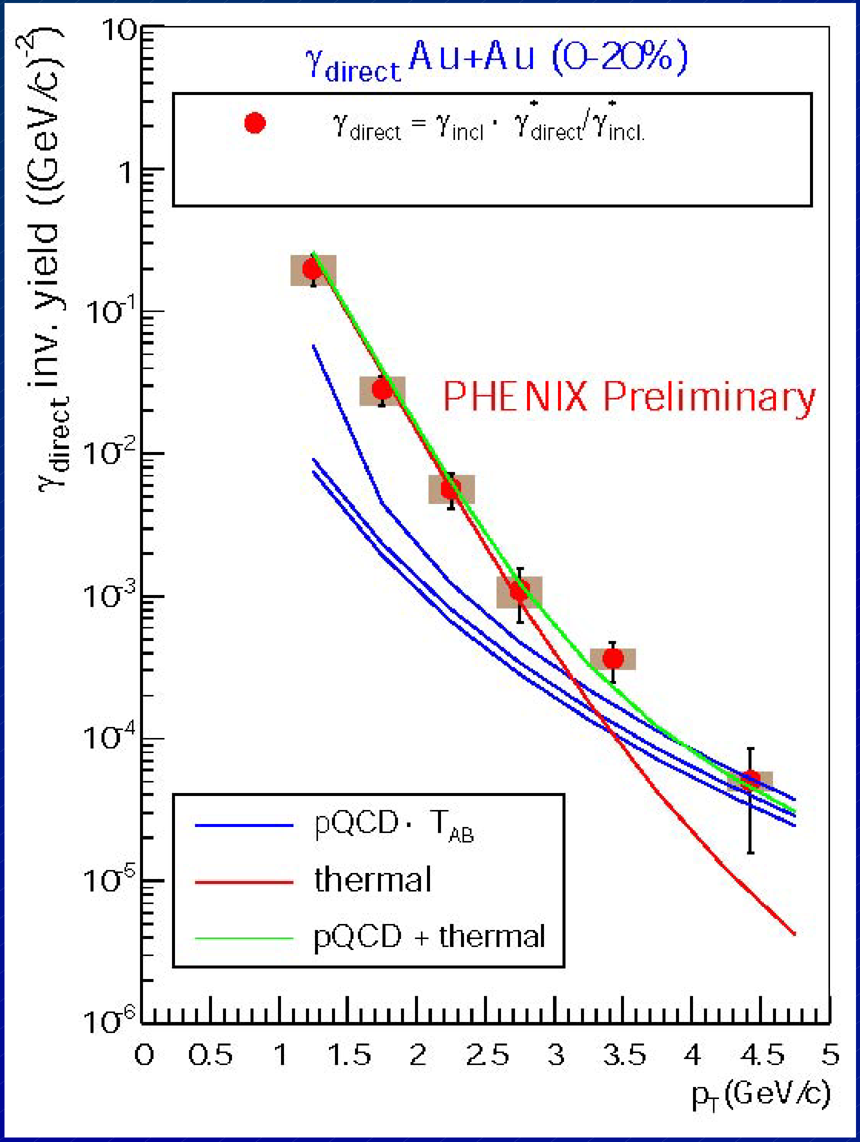


Measured ratio

$$\frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{incl.}}} = \frac{R_{\text{data}} - R_{\pi^0+\eta}}{R_{\text{direct}} - R_{\pi^0+\eta}} = \frac{\gamma_{\text{direct}}}{\gamma_{\text{incl.}}}$$

From conventional measurement

The spectrum



- Compare to NLO pQCD
  - L.E. Gordon and W. Vogelsang
  - Phys. Rev. D48, 3136 (1993)
- Above (questionable) pQCD
- Compare to thermal model
  - D. d'Enterria, D. Peressounko
  - nucl-th/0503054

2+1 hydro

T_0^{ave}=360 MeV (T_0^{max}=570 MeV)

τ_0=0.15 fm/c

- Data above thermal at high p_T
- Data consistent with thermal+pQCD
- Needs confirmation from p+p measurement

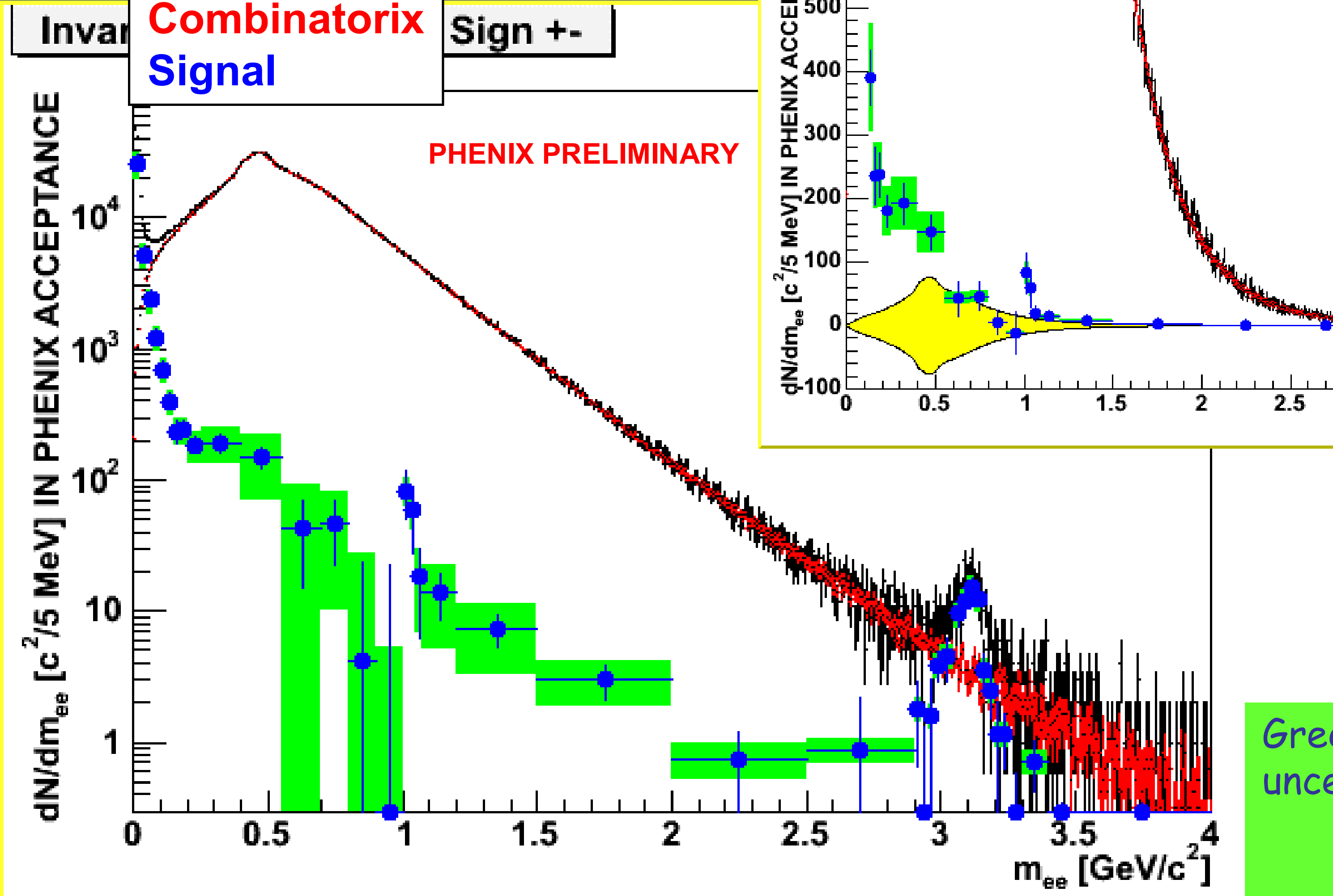
- Photons measurements
  - Calorimeter measurement
  - Beam pipe conversions
  - Internal conversions
- **Dielectron continuum**

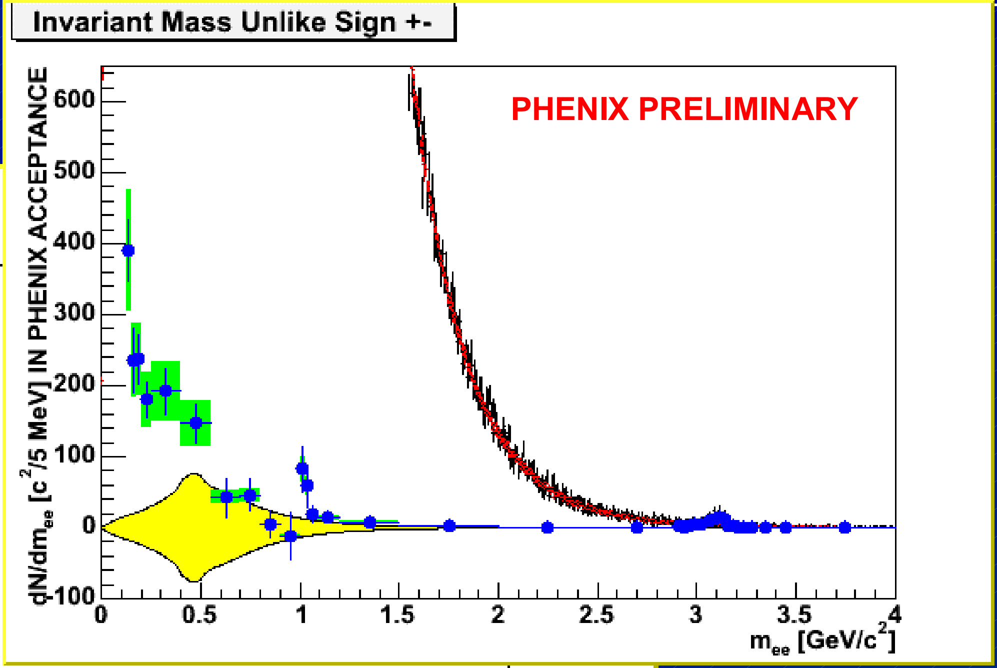
Dielectron spectrum

Integral:180,000
above π^0:15,000

BG normalized to
Measured like sign yield

All the pairs
Combinatorix
Signal

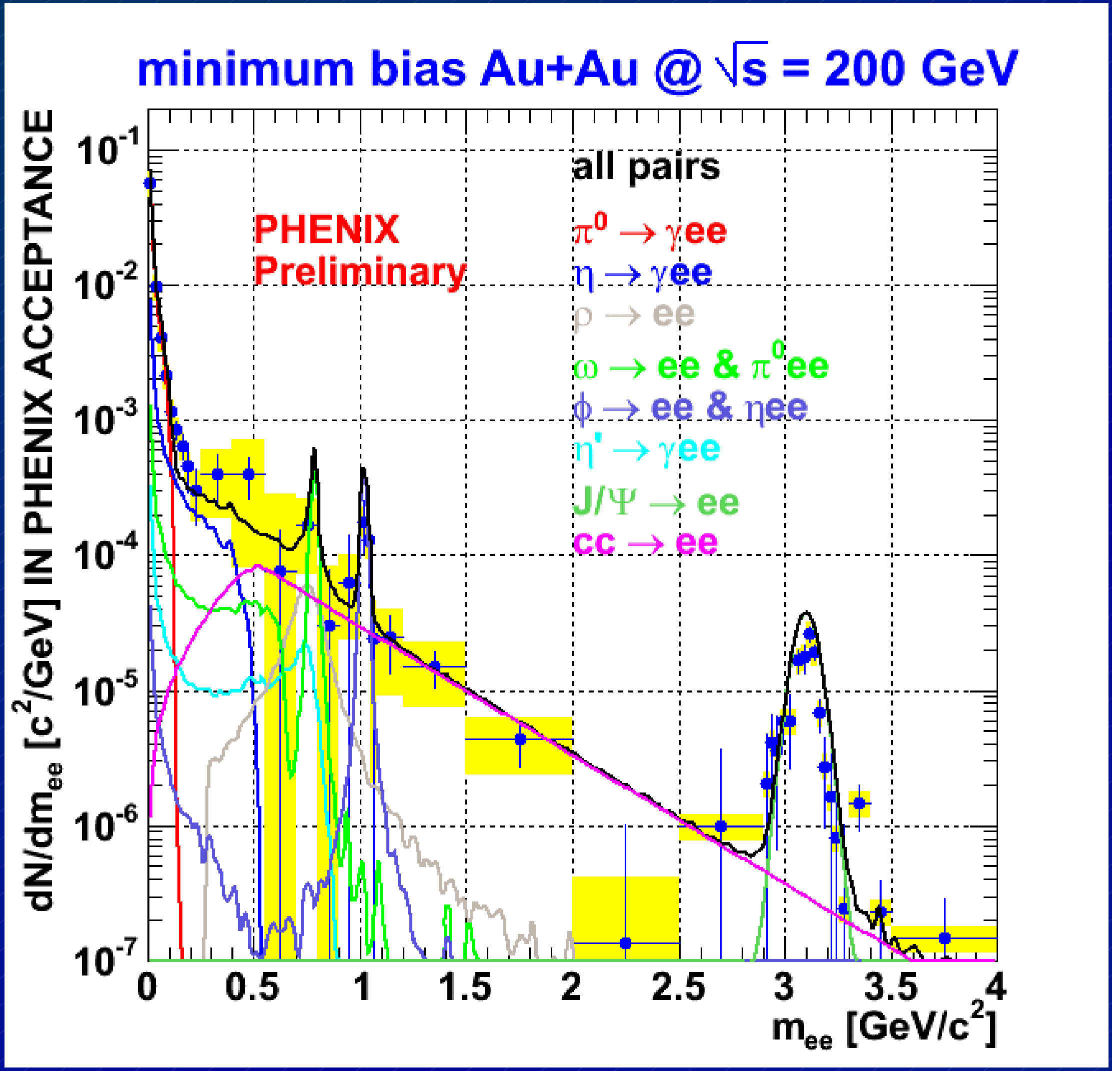


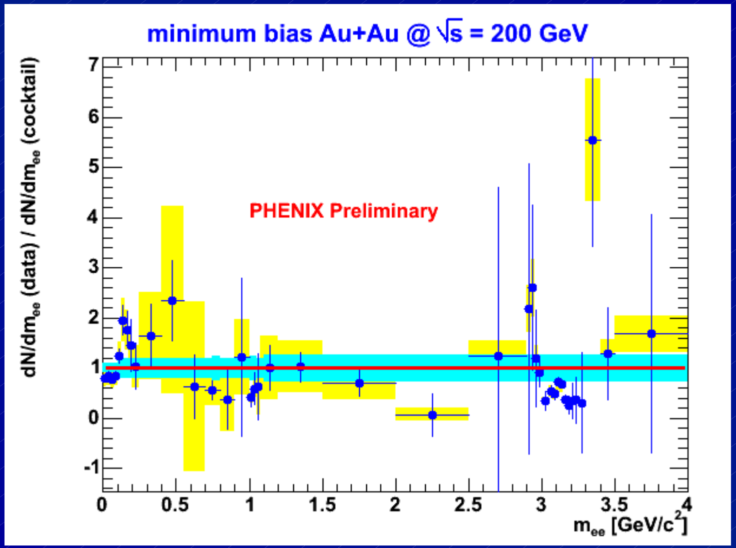


For details, see poster presentation by A. Toia

Green band: systematic uncertainty
- Acceptance
- Efficiency
- Run-by-run

Cocktail comparison





A prediction (Rapp, nucl-th/0204003) says direct thermal radiation is about the same as charm contribution in 1-2GeV/c², and it will be dominant as we go to higher p_T…

- **Data and cocktail absolutely normalized**

- Cocktail from hadronic sources
- Charm from PYTHIA

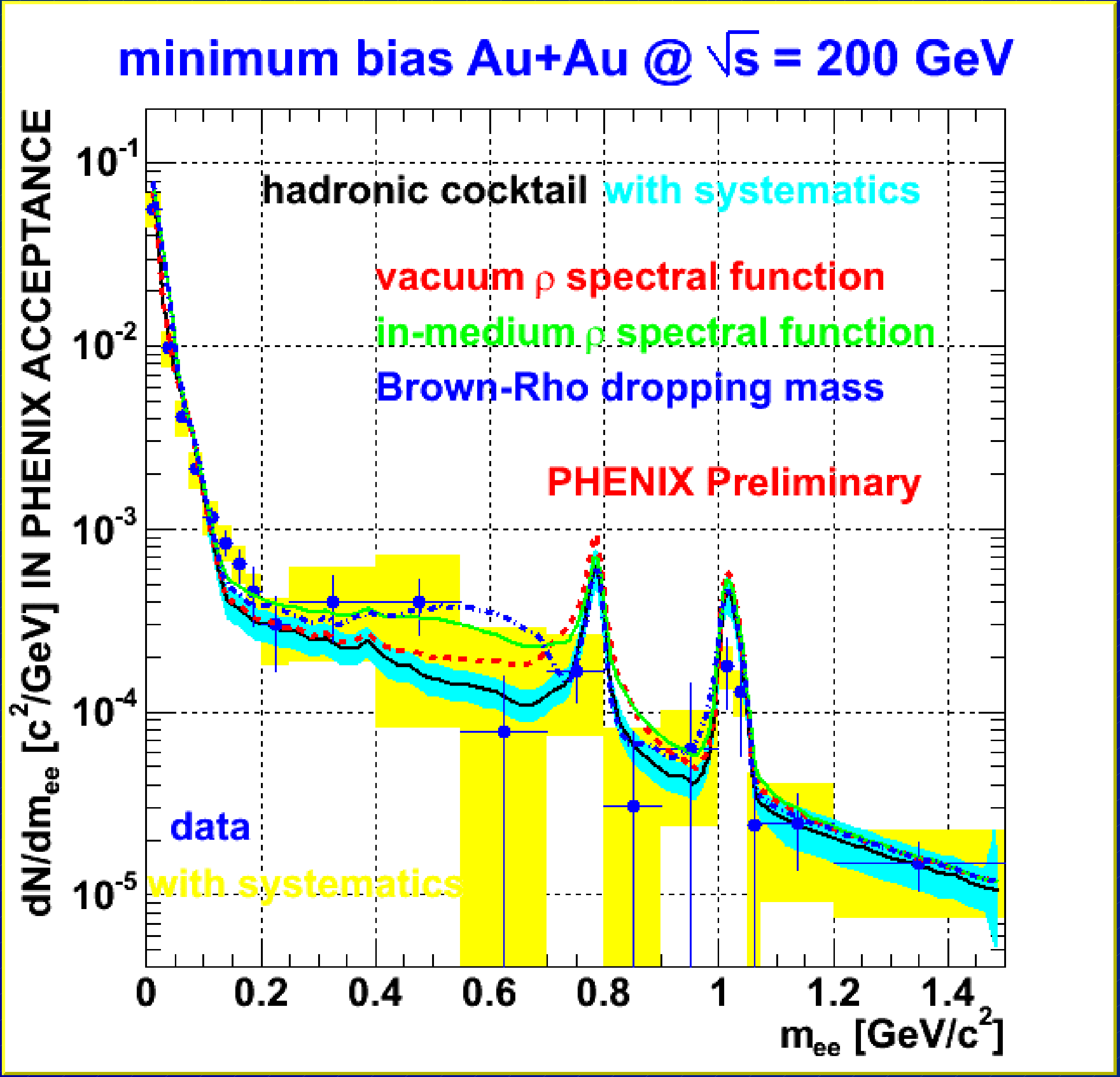
Predictions are filtered in ***PHENIX acceptance***

- **Low-Mass** Continuum:

hint for enhancement not significant within systematics

- **Intermediate-Mass** Continuum:
  - Single e → p_T suppression
  - Angular correlations unknown
  - Room for thermal contribution?

Comparison with theory



- calculations for min bias
- QGP thermal radiation included

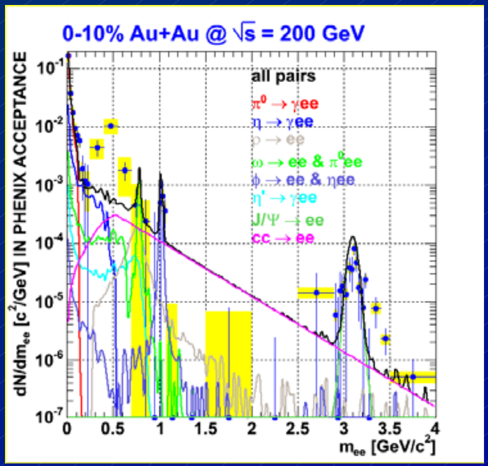
- Systematic error too large to distinguish predictions
- Mainly due to S/B
- Need to improve

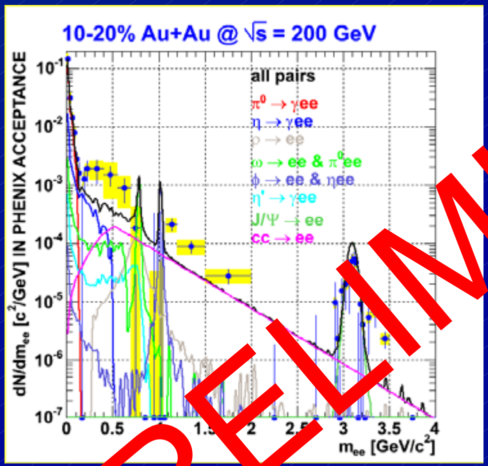
→ Hadron Blind Detector will improve S/B up to a factor 100

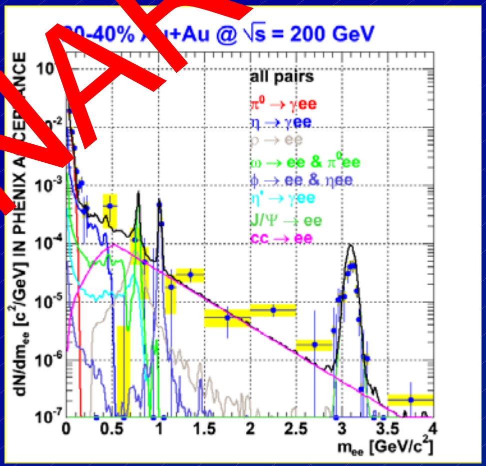
R.Rapp, Phys.Lett. B 473 (2000)
R.Rapp, Phys.Rev.C 63 (2001)
R.Rapp, nucl/th/0204003

Different centralities

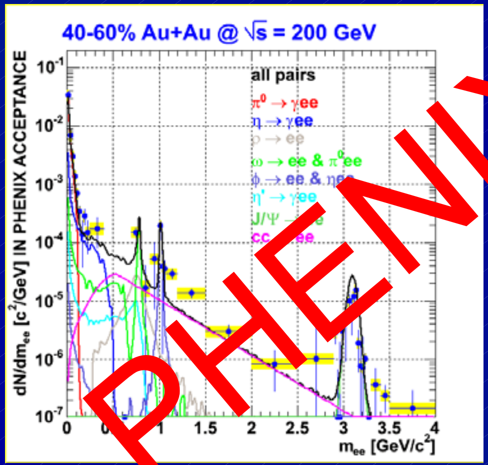
0-10% | 10-20% | 20-40%

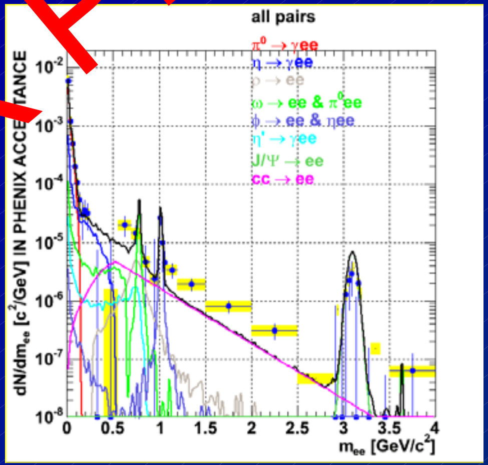






40-60% | 60-100%

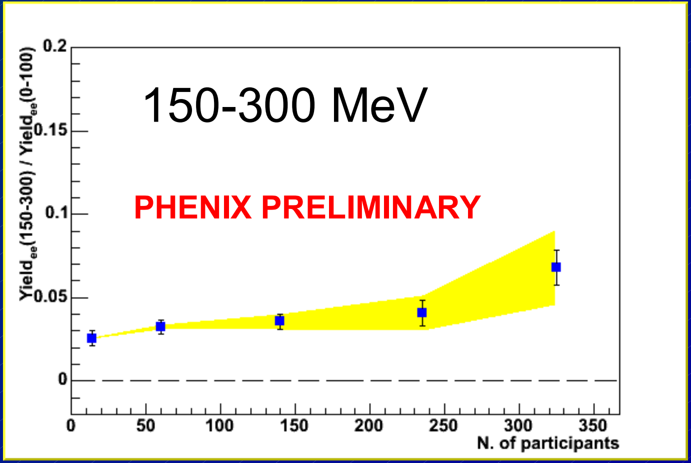


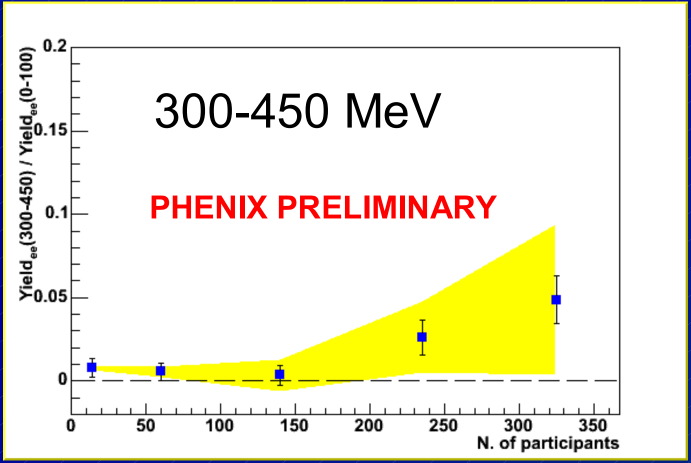


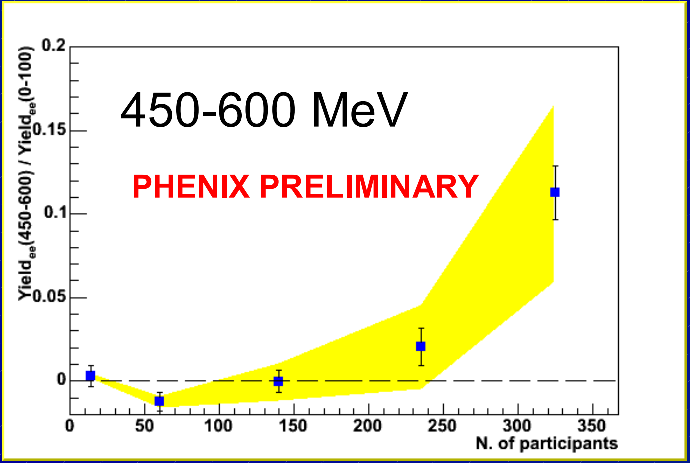
PHENIX PRELIMINARY

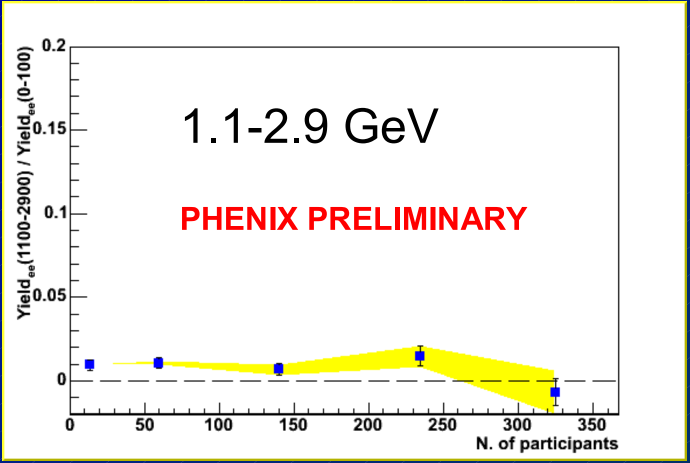
Mass ratios (A-B)/(0-100 MeV)

Ratio of different mass intervals to π^0 yield (0-100 MeV)









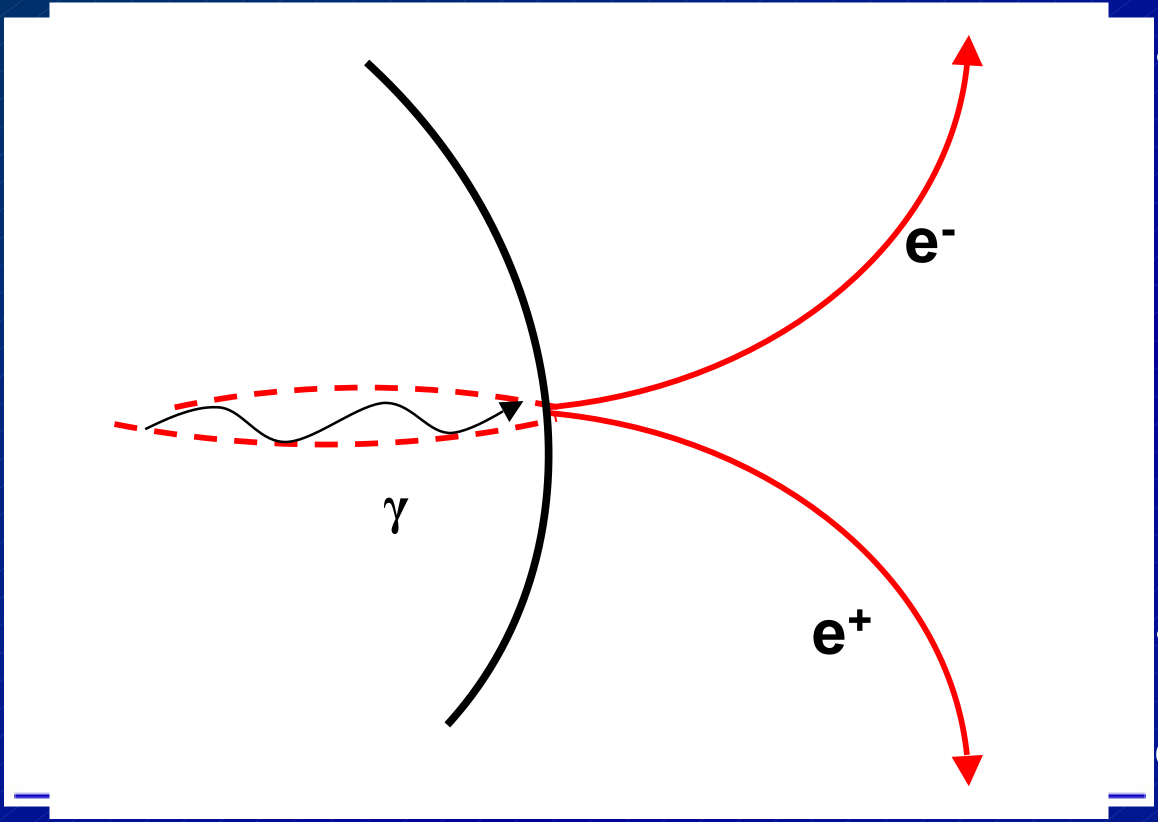
Summary

- Electrons and photons are penetrating hard and soft probes for relativistic heavy ion collisions
- Real Photons
  - Calorimeter measurement
    - Direct Photons measured in p+p in agreement with NLO pQCD
    - No initial state effects on direct photon production observable in d+Au (higher statistics run needed)
    - Photons are not suppressed in Au+Au, therefore observed hadron suppression is medium effect
    - Systematic uncertainties at low p_T too large to make definite statement about thermal photon contribution
  - Beam pipe conversions: A chance to see thermal photons?
  - Internal conversions
    - Promising new technique to measure direct photons
    - Thermal photon scenario consistent for pT<3GeV/c
    - Same analysis of p+p is needed as confirmation
- Dielectron continuum
  - hint for centrality-dependent excess not significant within systematics
    → Hadron Blind Detector upgrade
  - Attempt to look for a contribution of direct photon conversion in intermediate mass dilepton spectra
  - Looks not significant compared to predicted thermally radiated dilepton


PHENIX
OVER ONE BILLION SERVED

Backup

The PHENIX experiment



- electrons:
  - momentum reconstruction (1% resolution)
  - particle ID: RICH (loose cuts because clean signature of conversion peak)
  - same or opposite arms: different pT acceptance
- photons: EMCal (loose cuts →high efficiency ~ 98%)

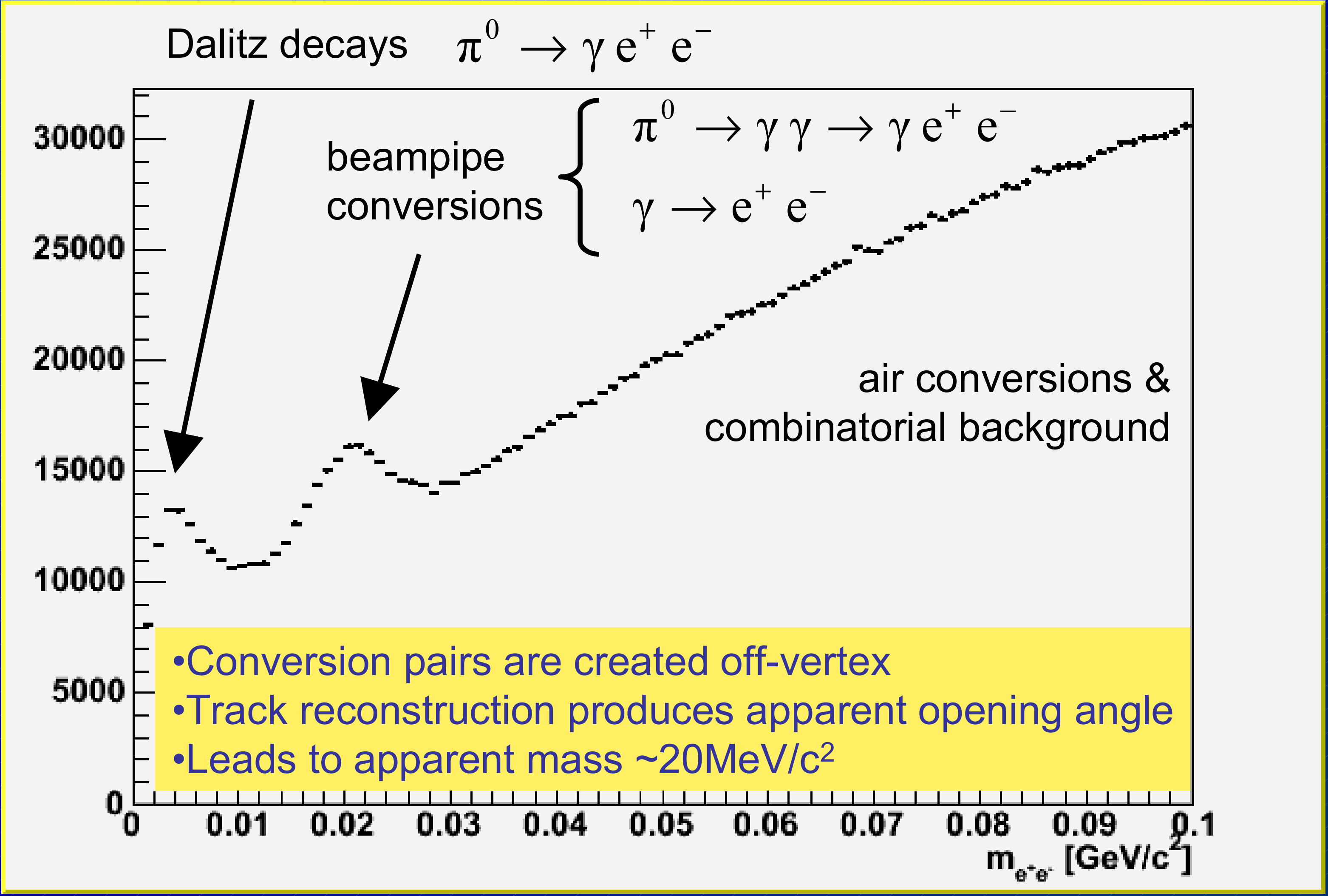
track reconstruction assumes vertex in the interaction point

→ conversion at radius $r \neq 0$: e+e- pairs 'acquire' an opening angle

→ they acquire an invariant mass $m = \int B\,dl \sim r > 0$

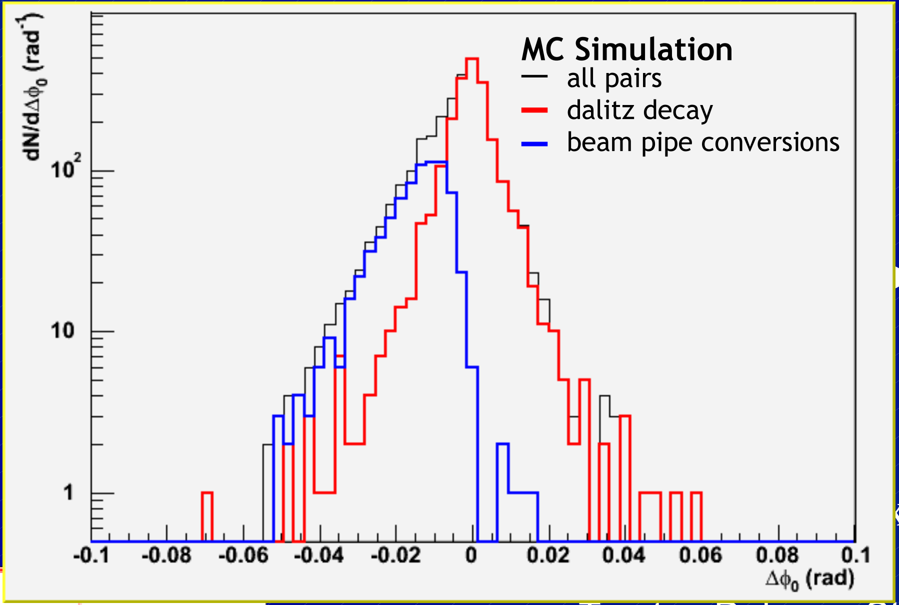
if r=4 cm (beam pipe) m =20 MeV

Invariant e⁺e⁻ mass spectrum of Run 4 Au+Au: $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$



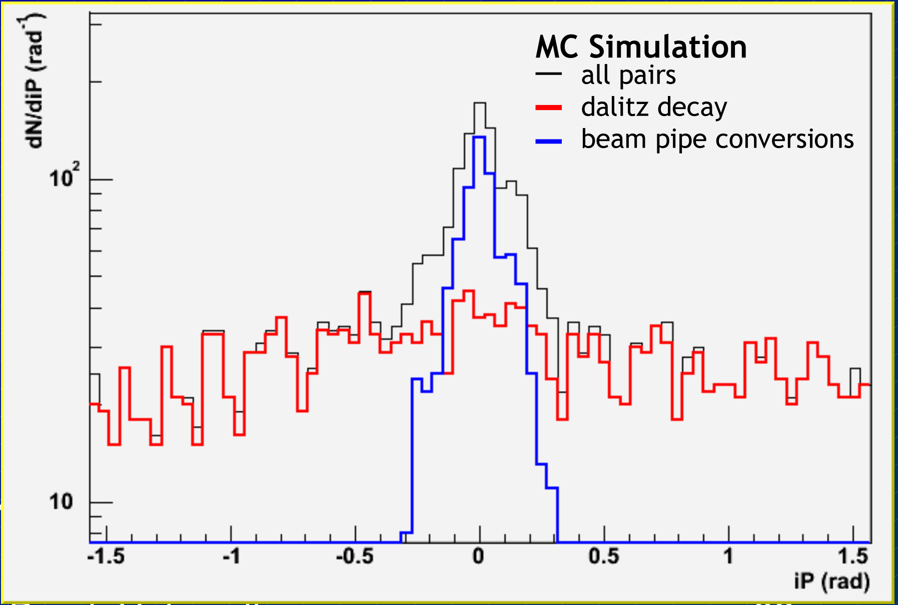
Pair properties

- Dalitz decays have a real opening angle due to the π^0 mass
- Conversion pairs have small intrinsic opening angle
  - magnetic field produces opening of the pair in azimuth direction $\Delta\varphi_0 = \varphi_0(e^-) - \varphi_0(e^+) < 0$
  - orientation perpendicular to the magnetic field



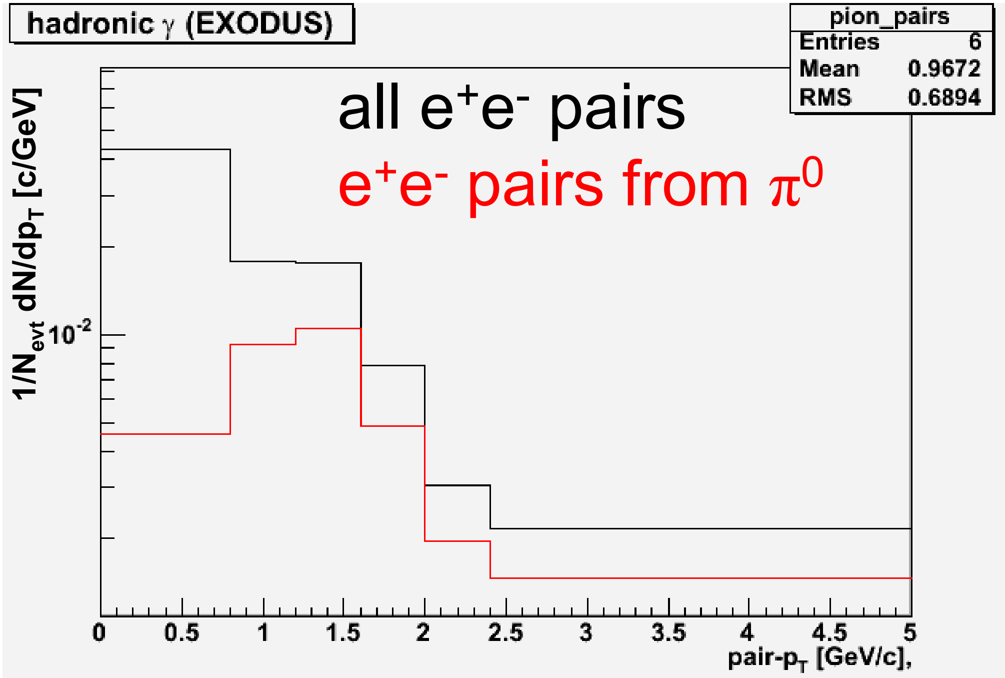
y

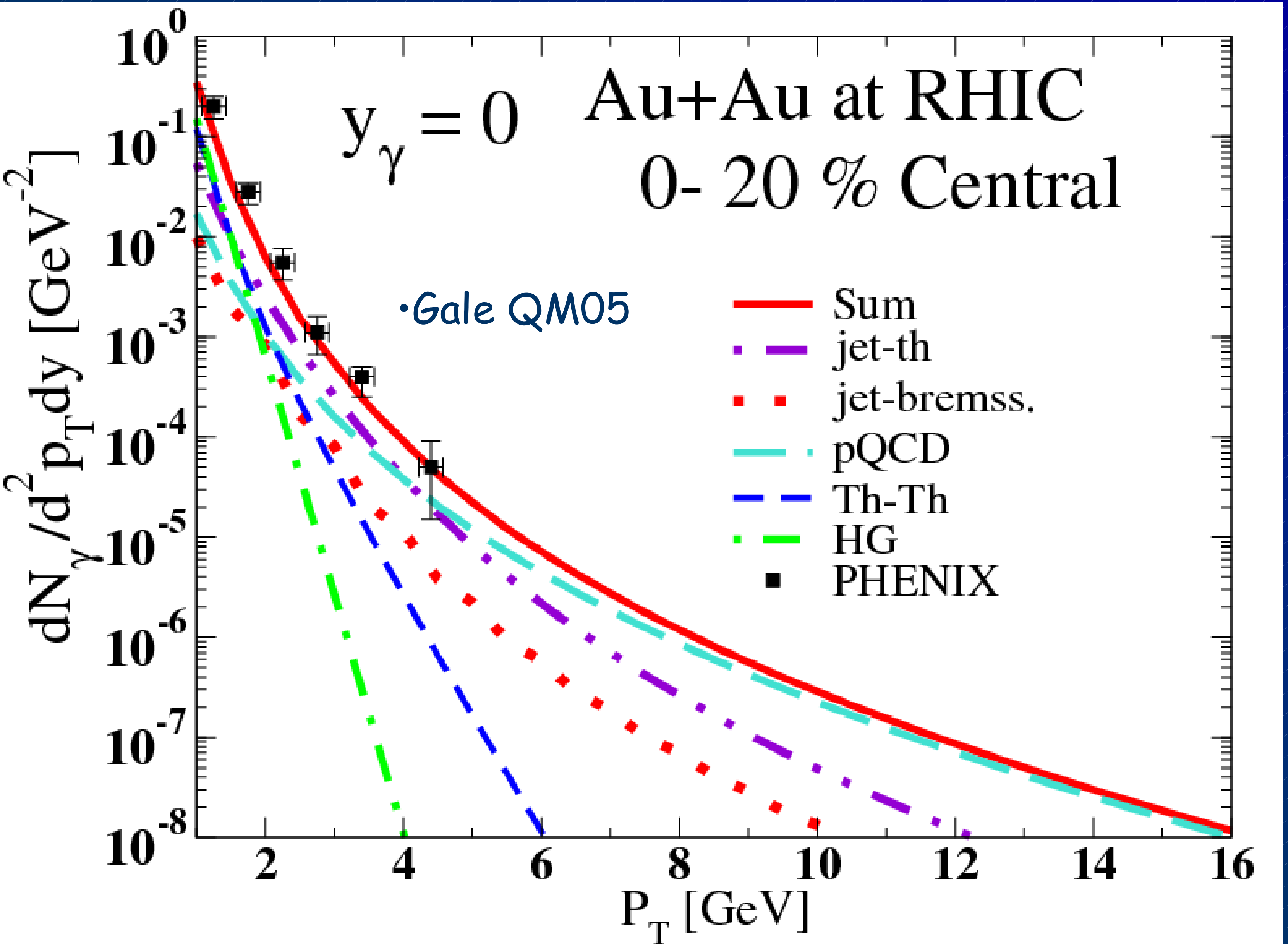
x



Simulations: $N_\gamma^{hadr}(p_T)$ and $N_\gamma^{\pi^0\ tag}(p_T)$

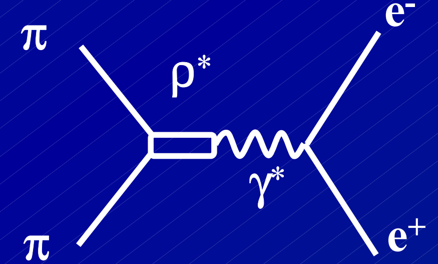
- Inclusive photon spectrum
  - $\pi^0, \eta \rightarrow \gamma e^+e^-$
    - π^0 parameterization from measured data
    - η from m_T scaling, yield normalized at high p_T (0.45 from measurement)
  - Use Dalitz decay ($\pi^0 \rightarrow \gamma\ \gamma \sim \pi^0 \rightarrow \gamma\ \gamma^* \rightarrow \gamma e^+e^-$ for $p_T > 0.8$ GeV/c)
- All e^+e^- (from π^0, η) in the acceptance → p_T spectrum of e^+e^-
- If γ from π^0 is also in acceptance →p_T spectrum of e^+e^- from π^0




Au+Au at RHIC
0- 20 % Central
$y_\gamma = 0$
•Gale QM05
Sum
jet-th
jet-bremss.
pQCD
Th-Th
HG
PHENIX
dN_γ/d^2p_Tdy [GeV^{-2}]
P_T [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
2
4
6
8
10
12
14
16

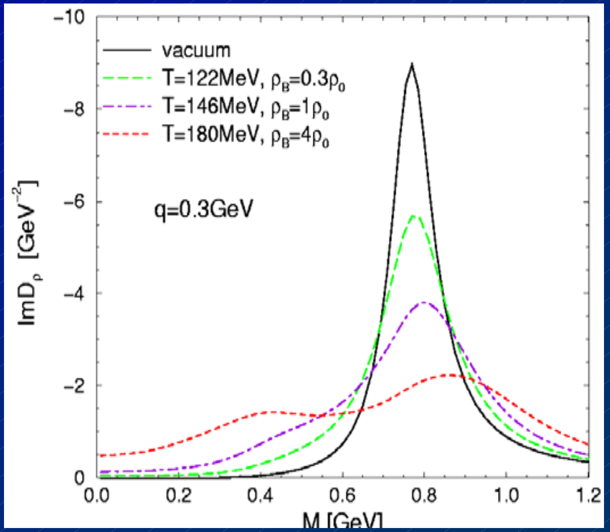
Theoretical calculation of π-π Annihilation

>> 100 publications since 1995

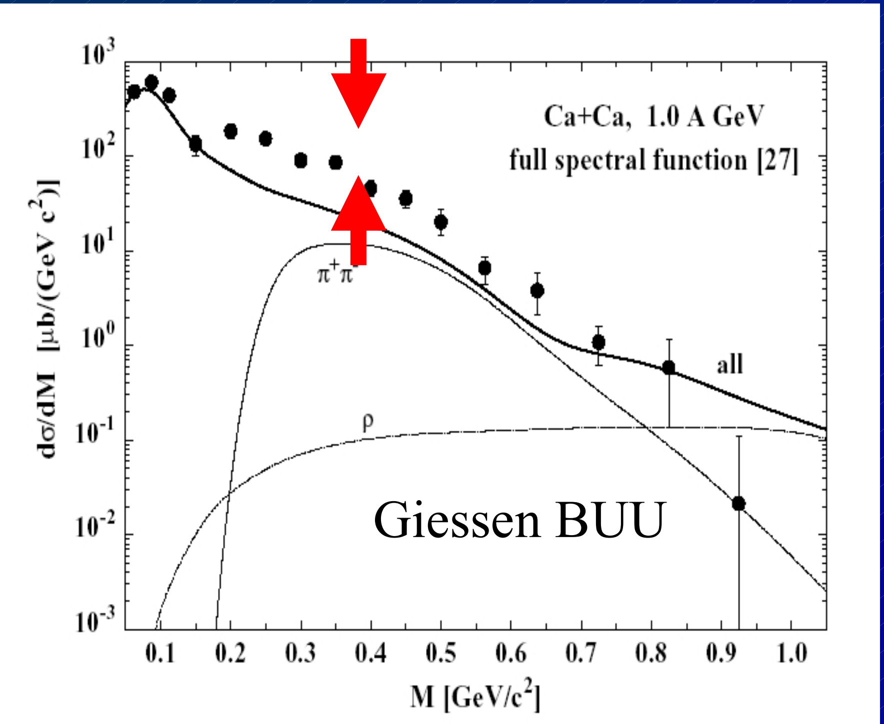


$$\frac{m_\rho^*}{m_\rho} \approx \left(\frac{<\bar{q}q>_{\rho^*}}{<\bar{q}q>_0} \right)^{1/3} = 1 - 0.16 \frac{\rho^*}{\rho_0}$$

- Low mass enhancement due to $\pi\pi$ annihilation
  - Spectral shape dominated ρ meson
- Vacuum ρ propagator
  - Vacuum values of width and mass
- In medium ρ propagator
  - Brown-Rho scaling
    - Dropping masses as chiral symmetry is restored
  - Rapp-Wambach melting resonances
    - Collision broadening of spectral function
    - Only indirectly related to chiral symmetry restoration
  - Medium modifications driven by baryon density
- Model space-time evolution of collision
  - Different approaches
  - Consistent with hadron production data
  - Largest contribution from hadronic phase



Dielectron pairs –the history I
low energy

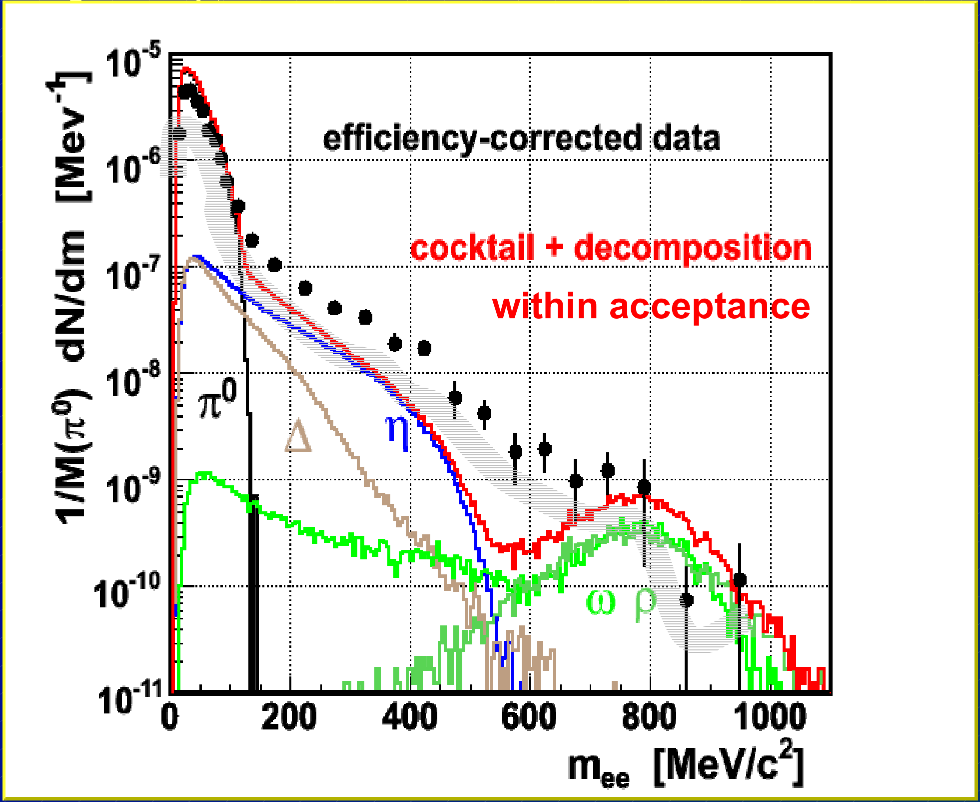


Data: **R.J. Porter et al.:** PRL 79 (1997) 1229
BUU model: **E.L. Bratkovskaya et al.:** NP A634 (1998) 168
transport + in-medium spectral functions

DLS measured an excess of dielectron pairs over the expected yield
Never fully explained

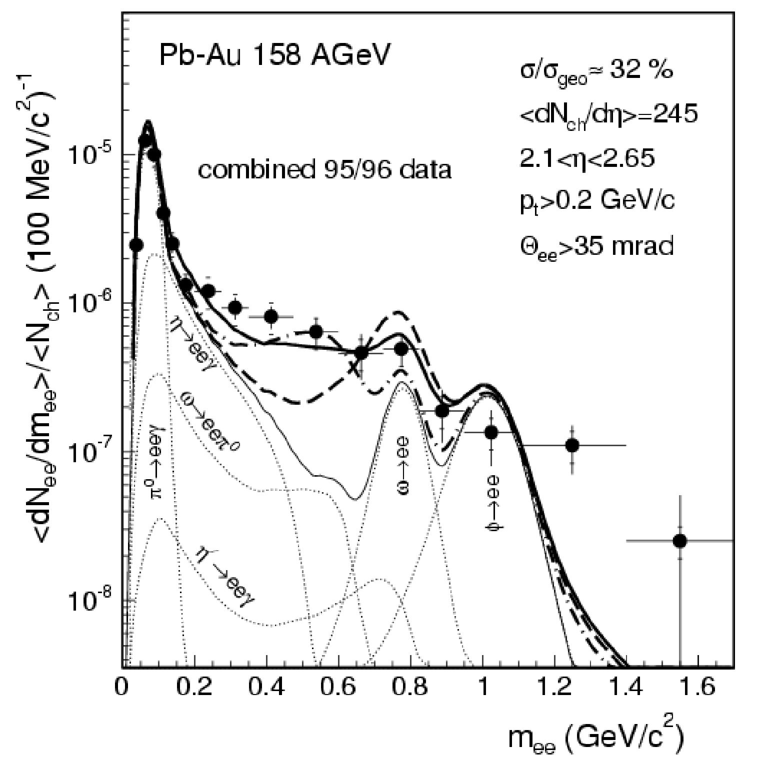
→ DLS puzzle !?

HADES (high acceptance, resolution, rate capability): first measurements

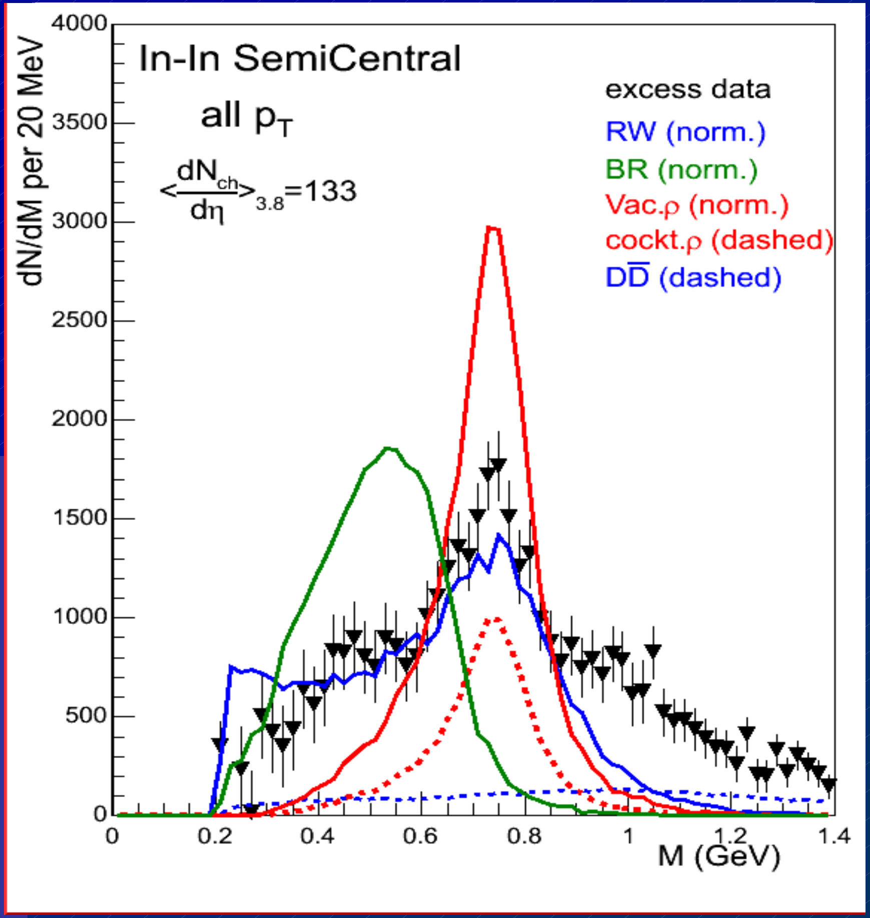


Excess over standard known sources compared with theory calculations
Comparison with DLS ongoing

Dielectron pairs –the history II high energy



CERES measured an excess of dielectron pairs over the expected yield
Attributed to ρ spectral function from ππ annihilation



NA60

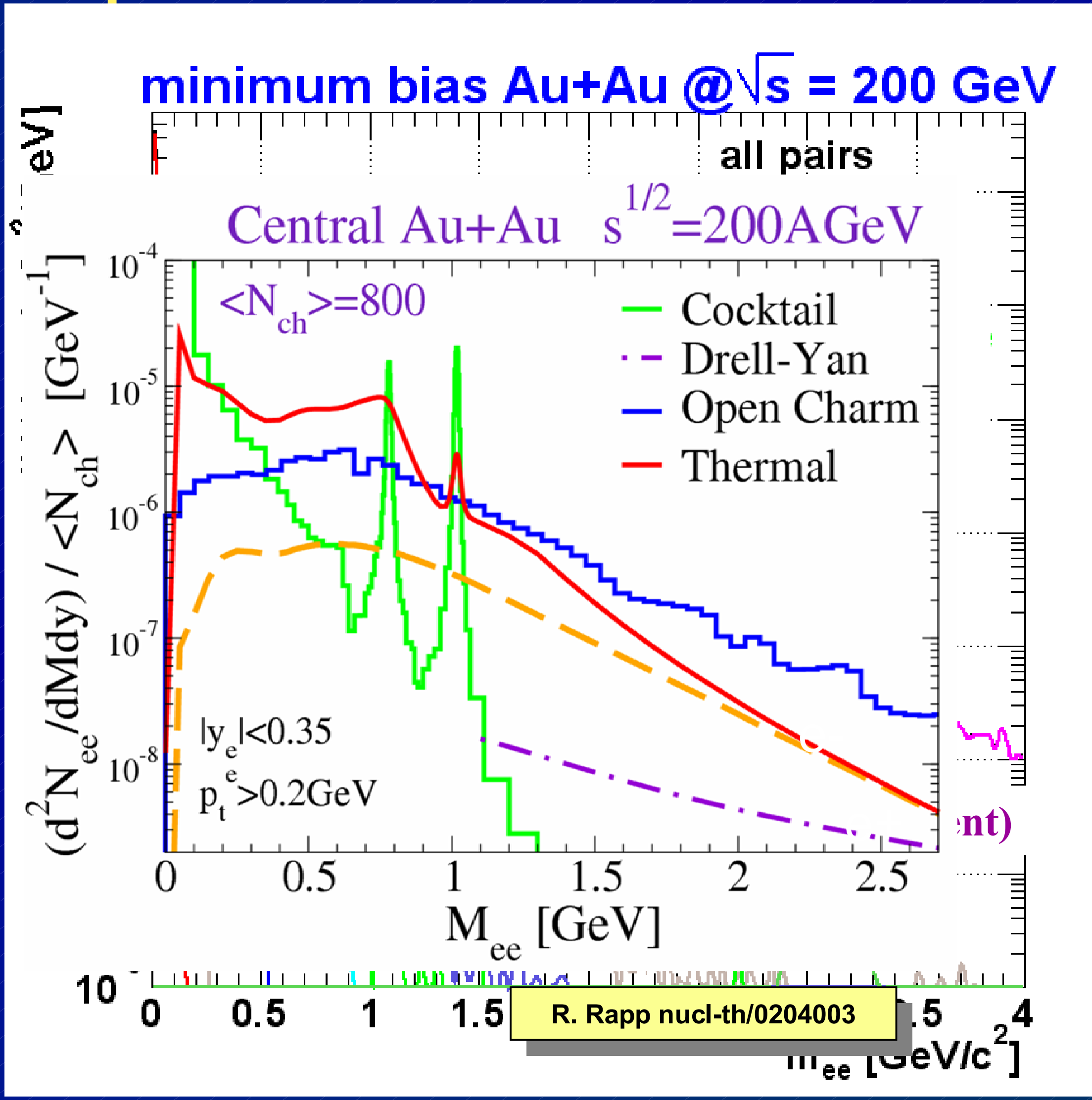
η : set upper limit ("saturating" the yield ~ 0.2 GeV
→ lower limit for the excess at very low mass
ω and f : fix yields to get a smooth underlying continuum

→first measurement of the r spectral function
Clear excess above the cocktail ρ, centered at the nominal ρ pole and rising with centrality
Rule out interpretations…

Dielectron pairs at RHIC

Expected sources

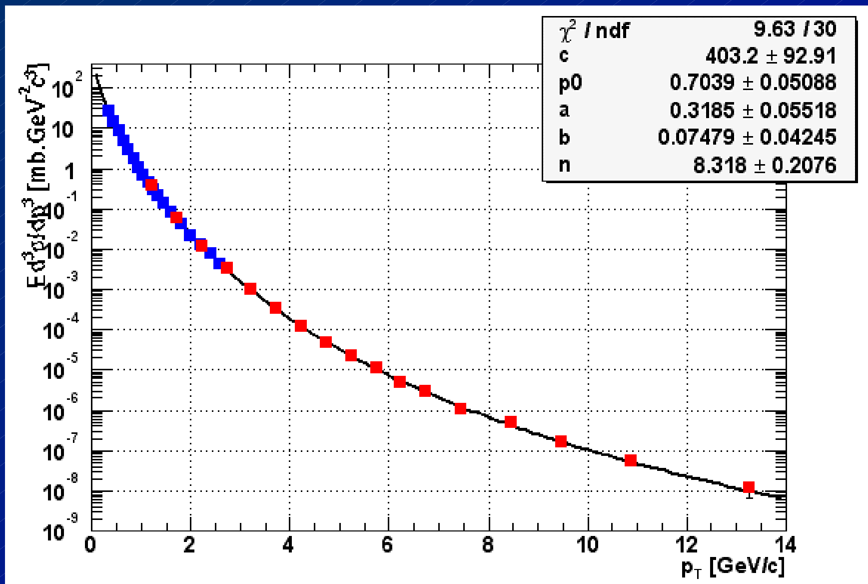
- **Light hadron decays**
  - Dalitz decays π^0, η
  - Direct decays ρ/ω and ϕ
- **Hard processes**
  - Charm (beauty) production
  - Important at high mass & high p_T
  - Much larger at RHIC than at the SPS
- **Cocktail of known sources**
  - Measure π^0,η spectra & yields
  - Use known decay kinematics
  - Apply detector acceptance
  - Fold with expected resolution



Cocktail ingredients (pp): π^0

- most important: get the π^0 right (>80 %), assumption: $\pi^0 = (\pi^+ + \pi^-)/2$
- parameterize PHENIX pion data:

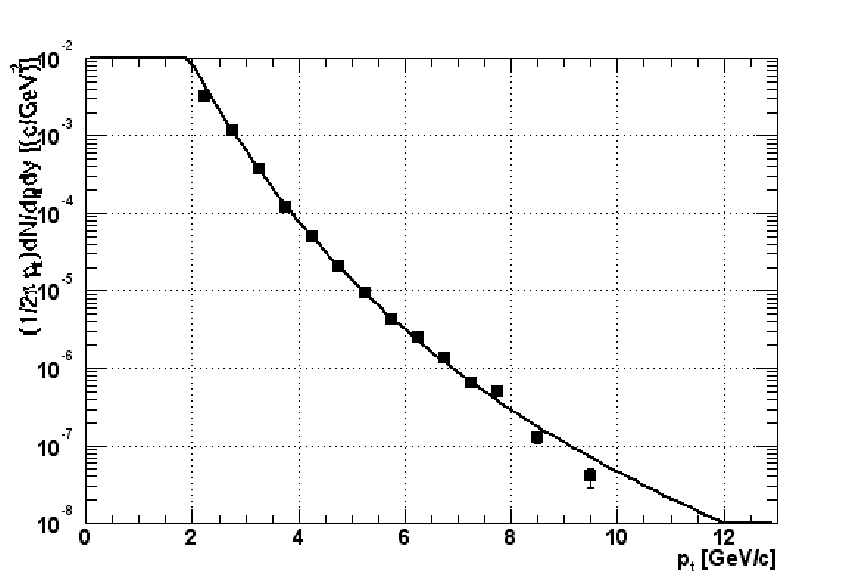
$$E\frac{d^3\sigma}{d^3p} = \frac{c}{\left(\exp(-ap_T - bp_T^2) + p_T/p_0\right)^n}$$



- most relevant: the η meson (Dalitz & conversion)
- also considered: ρ, ω, η′, ϕ
- use mT scaling for the spectral shape, i.e.

$$p_T \rightarrow \sqrt{p_T^2 + m_{meson}^2 - m_\pi^2}$$

- normalization from meson/π^0 at high pT as measured (e.g. $\eta/\pi^0 = 0.45 \pm 0.10$)



Combinatorial background I

Which belongs to which? **Combinatorial background**

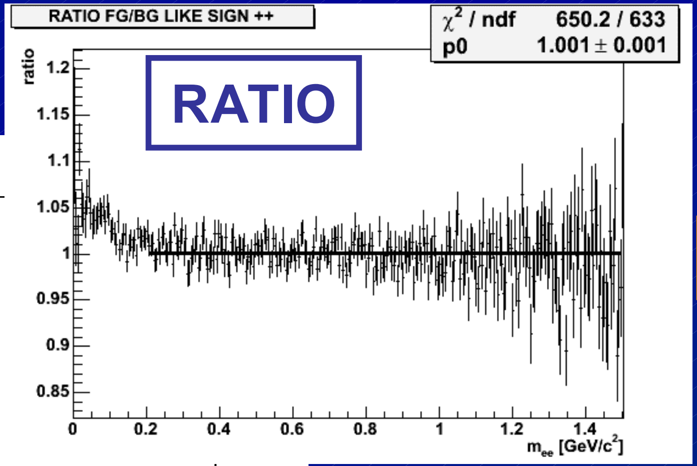
$\gamma \rightarrow e+ e-$ $\gamma \rightarrow e+ e-$ $\gamma \rightarrow e+ e-$ $\gamma \rightarrow e+ e-$

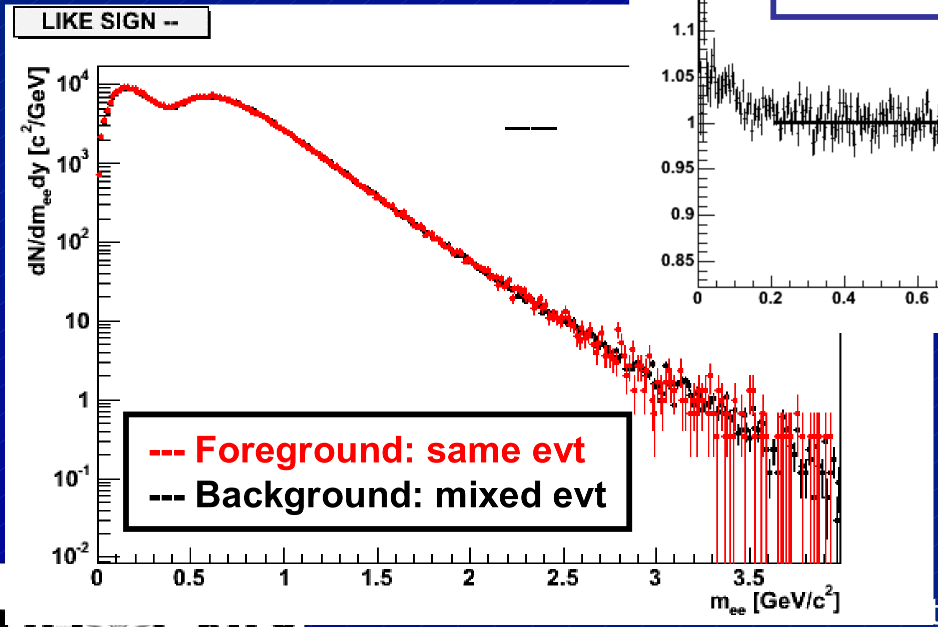
$\pi^0 \rightarrow \gamma\, e+ e-$ $\pi^0 \rightarrow \gamma\, e+ e-$ $\pi^0 \rightarrow \gamma\, e+ e-$ $\pi^0 \rightarrow \gamma\, e+ e-$

PHENIX 2 arm spectrometer acceptance:

$dN_{like}/dm \neq dN_{unlike}/dm$ → different shape → need event mixing

like/unlike differences preserved in event mixing → Same normalization for like and unlike sign pairs





BG fits to FG 0.1%

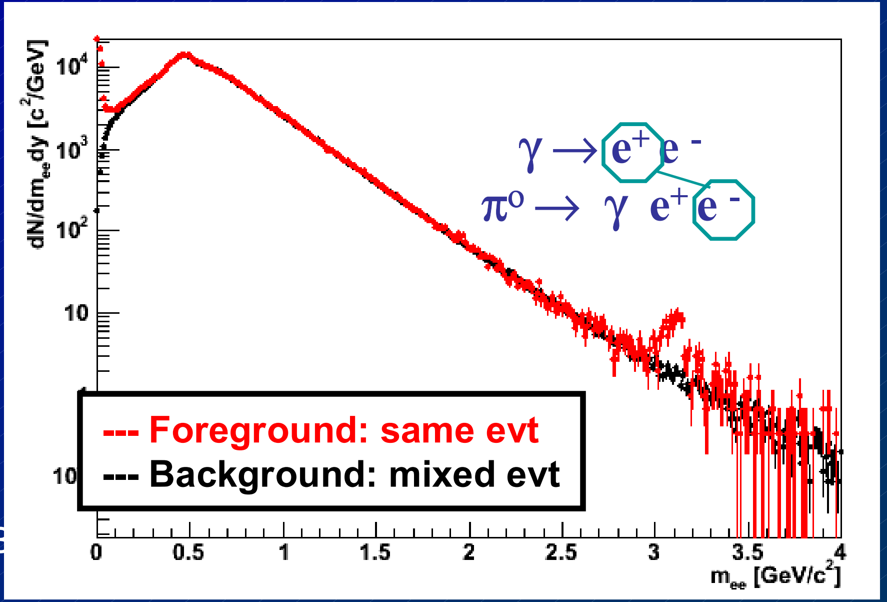
In all centrality bins

Combinatorial background II

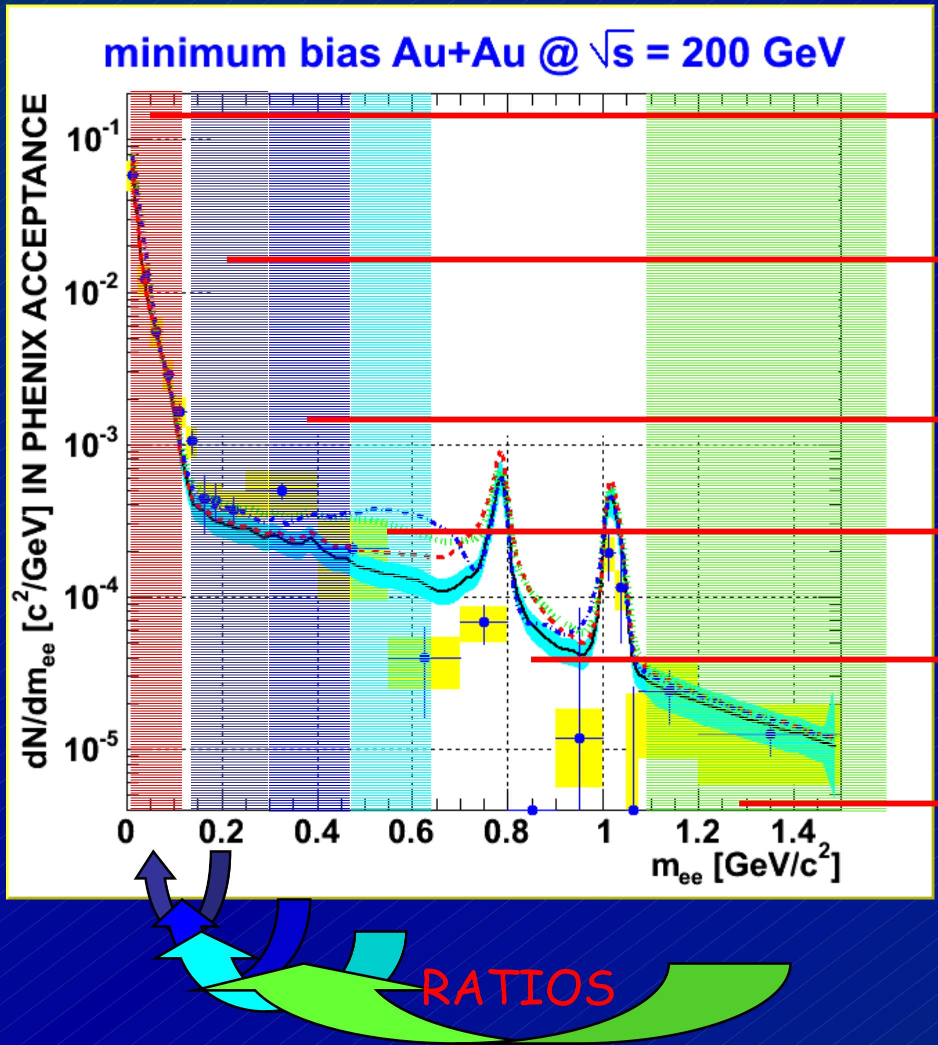
- Different independent normalizations used to estimate sys error
  - **Measured like sign yield:** **Real++,-- / Mixed++,--**
  - **Event counting:** **Nevent / Nmixed events**
  - **Geometrical Mean:** **$N\pm = 2\sqrt{N{+}{+}N{-}{-}}$**
  - **Track counting:** **$\langle N\pm\rangle = \langle N+\rangle\langle N-\rangle$**

- After all required corrections,
  all the normalizations agree within 0.5%

Systematic uncertainty: ±0.25%



Mass ratios (A-B)/(0-100 MeV)



0-100 MeV: π^0 dominated; scales with N_{part}

150-300 MeV: η dominated + continuum

300-450 MeV: still η + continuum

450-600 MeV: only continuum

600-1000 MeV: sorry, no significant measurement here ☹

1.1-2.9 GeV: charm dominated; scales with N_{coll}